Technological Persistency of Inorganic Solid-State Lighting Systems

A Comprehensive Approach for Assessing Criticality Dimensions of Innovative Lighting Technologies

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Executive Summary

In view of expected rising energy demands for lighting around the world and in the European Union, efficient technologies for the generation of synthetic light help to mitigate resource consumption. Light-emitting diodes pose a promising technological approach to provide sustainable infrastructure for domestic-, industrial/commercial- and public lighting. This thesis discusses the potential of light-emitting diodes for sustained use in comparison to conventional lighting technologies.

However, the achievement of this objective is challenging. A conventional concept of sustainability does not provide the right conceptualities in order to assess technological solutions and their technical implementations on grounds of their future viability. Therefore the concept of technological persistency is introduced as an adjusted strategy for assessment. It adapts the areas of activity, which constitute the three basic pillars of sustainable development to fit a technology-related, function-specific context: environment, economy and society are modified in order to suit the requirements of assessing sustainability in lighting. Consequently the derived major subjects of technological persistency are constituted by the core factors energy, material and function. Subsequent assessment is conducted on the basis of a set of subordinate sub-factors of high topical relevance. The reconciliation of technical specifications, resource strategic considerations and functional properties represents the main challenge of this approach. Hence a methodology of assessment is developed that takes thematic differences into account. By combining all assessment factors in a balanced and comprehensive analysis, the strengths and weaknesses of the considered technological/ technical solutions become evident. The assessed solutions comprise established conventional lighting technologies as points of reference and a selection of various LED-based lighting units designed for domestic, commercial and public applications.

The results show that LED-based lighting systems represent favourable solutions with regard to the aim of energy conservation. By offering efficient transformation of energy into visible light and unparalleled durability they clearly surpass conventional light sources like incandescent lamps and gas discharge lamps. Also with regard to functional properties, solid-state lighting achieved gains and is now on par with previously prevailing lighting systems. Yet those advantages are accompanied by increased complexity. LED light sources represent intricate devices, which require the use of raw materials with unique properties and highly specialized functional materials. As production of LED illuminants is projected to increase in the near future, the availability of those materials might be uncertain. Regarding materials demand, the disassembly of the evaluated illuminants showed that resource usage is strongly dependent on technical implementation. Novel technical layouts and advances in LED fabrication therefore play an important role in providing more sustainable light sources for the future. In this way technological persistency of LED lighting can be further increased by enhanced efficiency, highly variable functionality and reduced consumption of materials.

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1 Motivation

To come to terms with the ever increasing need for raw materials, mankind needs to increase the effectiveness of resource usage. With regard to the problem of finite resources and their inhomogeneous distribution across our planet, it becomes evident that a careful strategic use of resources is needed to manage the extensive mass flows along global supply and value added chains. When humans mine for commodities in order to utilize resources, materials usage is always accompanied by transformations of matter. Often numerous refinement steps and processing are necessary to finally provide a usable product. Also when turning to scrap after the active phase of product use or during the utilization of recycled secondary raw materials those transformations of matter continue. Nearly nothing which is used remains in its original constitution, but is altered in many different ways.

Therefore the question arises whether the possibilities for transformation are limited by the available quantities of materials that can be transformed. For crude oil, nobody will deny the truth of this statement. The onset of the industrial revolution, which sparked the development towards our modern consumer societies was made possible by the exploitation of fossil fuels. It enabled humankind to overcome the growth boundaries that were imposed by environmental circumstances. Without tapping that vast resource of stored energy generated by millions of years of biomass growth, the huge increase in productivity necessary to facilitate the development of advanced technology and enhanced food production would not have been possible. In consequence mankind created a debt in energy that will someday decide if it was put to good use or if the opportunities to create a sustainable form of living have been squandered.

By creating structures that no longer require transformations of matter, civilization could maintain high standards of living for the foreseeable future. This especially applies for the generation of energy, which in turn will be used for further transformations. One of the key domains where the transition to matter-less transformations of energy could show its benefits is the generation of synthetic light. According to the European Commission currently about 86 TWH of energy are consumed by domestic lighting applications in the European Union (European Commission 2016).

Due to the fact that most of the electricity used to operate sources of synthetic light is generated by the combustion of fossil fuels, providing long lasting and efficient lighting devices and combining them with renewable energy sources could pose a major contribution in protection of the earth´s resources (Eurostat 2017). Insofar light emitting diodes (LEDs) can represent a seminal final link in a chain of matter-less energy transformation. Solid-state lighting might still be a young technology, but it bears great potential. Since the first introduction of white LEDs there have been remarkable improvements to both design and efficiency. In view of the development of increasingly efficient luminaires that nowadays even surpass compact fluorescent lamps the LED is expected to become the most relevant lighting technology in the future. Advantages in versatility and longevity as well as their robust design and nontoxic components are additional gains over existing light sources. In promoting the idea of matter-less transformations, the combination of light-emitting diodes and photovoltaics could provide sustainable infrastructure that, if once installed, will not require any additional transformation of material resources. This would constitute an elegant way in ensuring long-lasting availability of synthetic light with strongly reduced further exploitation of finite resources.

As synthetic light fulfils the purpose of being perceived by human beings, functional aspects complement the picture of infrastructural requirements. Illuminants meet low acceptance if they are not in compliance with human needs. Consequently in order to be viable technical solutions for the future, modern lighting systems need to offer good performances in terms of energy efficiency, usage of resources and functional properties. For this reason the considerations in this work are intended to deal with the question, to which extend LED lighting fulfils those requirements in comparison to established technologies.

2 Research Question

With regard to energy generation new demand situations (e.g. electric mobility, vertical agriculture) and a shift towards renewable energies in countries of the western hemisphere require measures to reduce energy consumption. Bearing in mind that general illumination uses a considerable portion of the energy produced within the European Union (Eurostat 2017), significant quantities could be saved by increased overall efficiency. Due to their widespread decentralized use and high volumes, illuminants leave much room for optimization. McKinsey (2012) states that by focusing on the promising and increasingly relevant LED-technology sustainable and energy efficient lighting can be further propagated. Reduced power consumption due to the application of solid-state lighting is accompanied by a reduction of power stations required to meet the overall demand in electricity (McKinsey 2012, p. 12-13). The implications of this process would be the reduction of transformations of matter, hence resulting in savings of energy and resources.

In view of the finite nature and potential instabilities of raw materials supply, the field of resource strategy is of great importance. As quality requirements on materials in more powerful light sources rise, it becomes necessary to utilize increasingly specialized material compounds as well to meet high standards in the course of their manufacturing. Shortages in supply regarding raw materials or precursors for the production of illuminants limit their availability for extensive use. Widespread application of more efficient and therefore more sustainable light sources is hence at risk.

Different sectors of illumination such as public lighting, industrial/commercial lighting and domestic lighting feature different functional priorities. A certain illuminant may be suitable for street lighting but on the other hand unacceptable for living room illumination. The human eye has different sensitivities for different wavelengths of the visible light spectrum. By designing light sources that take those physiological circumstances into account, the emitted radiation can be tuned to be more exploitable for human spectators. In utilizing spectral compositions that match the most sensitive regions of the eye, light sources with comparably low power output can appear brighter than those that waste energy by emitting less perceptible wavelengths (Schubert 2006, p. 280). This reduction of spectral quality brings benefits with regard to efficiency but might be less suitable for applications where a rich color impression is desirable. Workspaces or living areas for instance are spheres where good rendition of colors is a key requirement for application.

In summary energy efficiency, efficient usage of resources and functionality are decisive factors for the sustainable generation of synthetic light. As a result, the question arises how to combine those aspects in order to create a meaningful tool for assessing sustainability in lighting. Furthermore with regard to the different technologies currently available a well funded statement about their individual suitability for sustained use is most welcome.

This work is dedicated to the development and implementation of such a tool. It carries out the necessary adaption of the concept of sustainability with the objective to make it applicable to lighting technologies for different sectors of use. This objective is however complicated by lack of applicability. The concept of sustainability does not provide the right conceptualities in order to assess technological solutions and their technical implementations on grounds of their future viability. Therefore the concept of technological persistency is introduced as an adapted strategy for assessment. It aims to incorporate the areas of activity, which are decisive for sustainable development in a technology-related, function-specific context. The areas of ecology, economy and society (core aspects of sustainability) are transferred to the subject matter of sustainability in lighting. In consequence the according major subjects of technological persistency are replaced by the core factors energy, material and function. Subsequent assessment is conducted on the basis of sub-factors with high relevance for the respective core factors. The reconciliation of technical specifications, resource strategic considerations and functional properties represents the main challenge of this approach. Hence a methodology of assessment is applied that takes account for those differences. By combining all assessment factors in a balanced and comprehensive manner the strengths and weaknesses of the considered technological/technical solutions become apparent.

3 Important Concepts of Resource Strategy

This chapter provides an introduction to the basic concepts of resource strategy. As this treatise is designed to address the problems that arise in assessing lighting technologies with regard to their sustainability, some of those concepts undergo a process of adaptation to comply with the topical demands. The following statements are based on the insights provided by technical literature. The most important sources are Grunwald and Kopfmüller (2012), Reller et al. (2013) and von Hauff (2014).

3.1 Resource Strategy

According to Reller et al. (2013) an effective strategy in handling the consumption, transformation and distribution of resources has the objective to identify as well as to implement a sustainable course of action. Utilizable transformations of materials and forms of energy have to be investigated for their long-term perspective. Deficits are to be eliminated in order to grant intelligent, ethical and sustainable forms of usage that are in correspondence with the aim to conserve the biosphere and to preserve the mineral resources of the geosphere. Under ideal conditions a permanently self-renewing balance between geo-, bio- and technosphere without irreversible losses would arise. With the very complex value-added chains and dynamic material streams of today, anticipatory strategies are a fundamental augmentation to static considerations. Advancing technological progress leads to the production of intricate devices that feature functional architectures of various materials stemming from geogenic, biogenic and fossil resources. Brought together by transport, transformation and composition those materials constitute the technosphere, which is nowadays characterized by globally interlinked technologies, structures and systems. Due to the undamped dynamic proliferation of modern technology this correlations become even more dynamic. The consumption of regenerative, mineral and fossil resources has reached an unprecedented magnitude and still increases. To keep track of those developments and to offer comprehensible methods of evaluation the concept of criticality was developed. As a part of resource strategic advisement it can be used as an instrument to identify short- to medium- term risks. It is also a tool to devise alternative approaches to solving resource-related difficulties and for assessing their feasibility. (Reller et al. 2013, p. 211-219)

3.2 Sustainability

As stated by Reller et al. (2013) sustainability is a term that has found its way into daily usage in many contexts. Apart from its actual intent as a technical term used to describe a certain way of acting it is readily employed by marketing agencies to impart a positive connotation to certain products or company arrangements. Despite its broad social spread few people are actually able to recite its exact meaning. This inflationary use also contributes to the general elusiveness of this term. Originally coined in silviculture, sustainability meant the prevention of exhaustive cultivation combined with the perpetuation or amendment of the status quo. In present use, the term attained a more abstract denotation and as it was introduced to various domains that involve the handling of resources. It has to be pointed out, that sustainability is not a perpetual condition. It should rather be understood as a process, which is subject to permanent change. Measures taken to increase sustainability in the past might not be suitable to do so in the present or future. Sustainable actions lead to sustainable development (Reller et al. 2013, p. 154-156). This development follows the fundamental paradigm to take responsible and reasonable action in order to ensure that following generations are able to freely choose their needs and lifestyles while preserving the needs of the current one (Grunwald and Kopfmüller 2012, p. 11). To reach this goal, it is necessary to include all three dimensions of sustainability: economy, environment and society (Reller et al. 2013, p. 158).

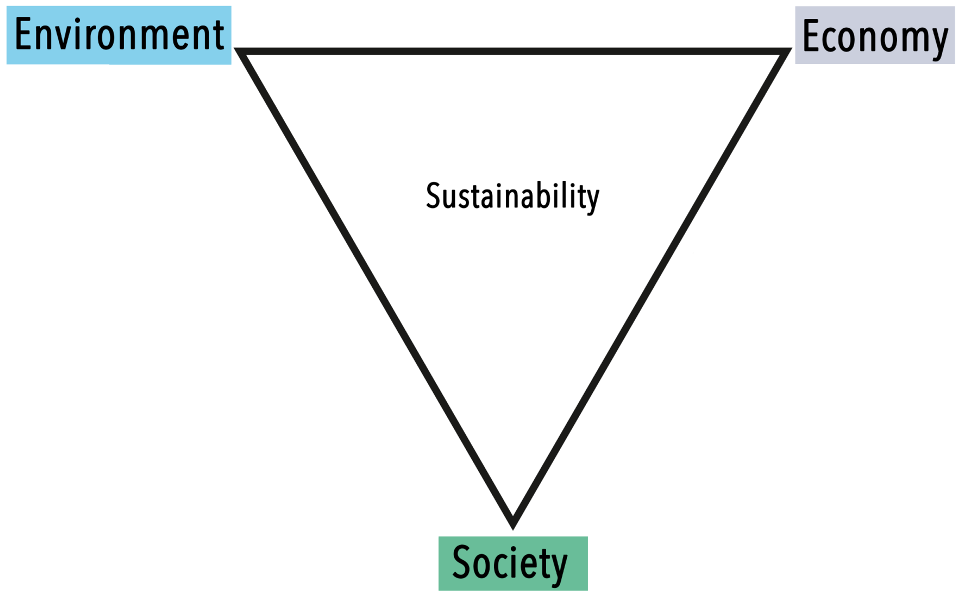


Fig. 1: The triangle of sustainability. (Reller et al. 2009)

Those three dimensions can be combined to from the so-called triangle of sustainability emphasizing the idea that equally incorporating those domains is of key importance. Only if protection of the ecosphere, a stable and predictable economic development and a fair distribution of livelihoods go hand in hand, a solid basis for sustainable development can result. As those basic dimensions can be subdivided into numerous sub-items, manifold aspects, which feature substantial interdependencies, add to the complexity of this topic (Reller et al. 2013, p.159). Aside from rather abstract considerations regarding intragenerational and intergenerational justice as well as the assessment of future developments and needs of mankind, more tangible spheres of activity can be identified.

With relation to this work, one of those spheres lies within the field of energy consumption. An important part in the effort to conserve the planets resources can be contributed by reducing the amount of energy consumed by applications of daily life. Since illumination is an omnipresent facet of human civilization, the advancement of efficient technologies to create synthetic light is of high relevance. However, not only the advancement of the technologies itself, but also the increasing variety of functional materials needed to implement them are part of this effort. Lighting is an essential part of the infrastructure on which modern industrialized countries base their foundation. Therefore, it is expedient to investigate the resource consumption involved in its provision. This way, one can determine if those innovative and energy-efficient technologies also can be classified as sustainable in terms of resource consumption. The third sphere is represented by functional profiles of lighting technologies. Acceptance for lighting products in terms of their functional properties with regard to the applications at hand also constitutes a decisive criterion for sustained use.

3.3 The Core Strategies of Sustainability

In his book "Nachhaltige Entwicklung" von Hauff (2014) formulates the core strategies of sustainable development. Those strategies are described in the following section. They are suitable to describe the correlations that have to be considered during the implementation of sustainable technologies. They are not to be regarded as independent guiding principles but as interdependent cornerstones of sustainable development (v. Hauff 2014, p. 61).

3.3.1 Efficiency

The strategy of efficiency aims for an increase in resource efficiency as well as resource productivity. With core issues like energy efficiency and the efficient usage of natural resources it can contribute to the relief on ecosystems from strains on their capacities. Since its combined economic and ecological advantages concerning the enhancement of resource-security and the relief on intake capacities of industrial sectors are of high relevance, it is the most operationalized core strategy. The strategy of efficiency, in a broader sense, correlates with the business case of sustainable economy. Enterprises can benefit from its implementation by cost reductions, which in turn can be reinvested in additional employment and raised workplace standards. Furthermore the strategy of efficiency can be interpreted as prevention of geopolitical crisis. Armed conflicts caused by growing resource scarcities are to be avoided by its mitigating effects. To overcome drawbacks like an exaggerated sense of technological optimism, it has to be supplemented by targets of mass-reduction in order to achieve ecological sustainability.

Technological progress has to be complemented by innovative lifestyles. This means that not only circumstances of production but also habits of consumption have to be involved on a broad basis to induce change. The most important as well as most present disadvantageous side-effect of the strategy of efficiency is the rebound effect. Possible savings are thwarted by increased consumption as a consequence of raised efficiencies. A descriptive example of this effect is the compensation or even overcompensation of increased fuel efficiency in cars by elevated mileages. (v. Hauff 2014, p. 62)

3.3.2 Consistency

The strategy of consistency is more demanding in its implication than the strategy of efficiency. It is also described by the term eco-effectiveness in some publications. This strategy comprises structural change in the scope of ecology applied on a micro- and macroeconomic level. Key aspects are promotion of new technologies, products and practices that are able to incorporate the cycle of materials that take part in industrial production into the metabolic cycle of natural ecosystems. Generally speaking, the impacts of human action should not disturb natural processes. This includes the demand for compatibility of man-made energy- and mass flows with inartificial flows. In an ideal case this implies that only reusable products reside in the sequences of the technosphere analogous to the cycles of the biosphere. Accordingly waste and emissions do not exist. If reincorporation into the cycles of matter is not possible the starting materials are no longer to be used. As opposed to the concepts of sufficiency and efficiency where non-renewable resources are rationed or rationalized respectively, the consumption of those resources is to be reduced or even avoided. In this way, future generations of the growing world population will still be able to satisfy their needs. To determine whether the strategy of consistency is applicable to real ecologic and economic systems an empiric approach has to be employed. For instance, some man-made environments are dependent on certain immissions causing the strict implementation of ecologic directives to be disadvantageous for the said cultural landscape. Hence this strategy not only necessitates the long-term adaption of both production and consumption patterns but also requires broad political measures exceeding the promotion of single technologies. A committed and foresighted policy of innovation that integrates social aspects is needed in order to facilitate adjusted useful change. (v. Hauff 2014, p. 63)

3.3.3 Sufficiency

The strategy of sufficiency is closely related to the strategy of efficiency. If it is disregarded, the peril of compensation or even overcompensation of gains in efficiency is existent. The superiority of LED illuminants in terms of efficiency over conventional lighting technologies provides exemplification: The savings achieved by the increased longevity and considerably higher energy efficiency of an LED compared to an incandescent bulb are counteracted by the acquisition of more light sources and increased overall illumination. This direct rebound effect can also be accompanied by an indirect effect. Instead of being converted into the acquisition of additional light sources, the monetary savings caused by higher energy efficiency are reinvested into the purchase of consumer goods that cause an increase in energy and resource consumption themselves. In order to cope with that, the strategy of sufficiency offers three basic solutions. Firstly self-restraint based on a voluntary decision is an acknowledged way to inhibit the impacts of the rebound effect. However in a system of market economy, this concept is not very well received because it stands in opposition to consumer sovereignty. The second component is represented by a change in lifestyle, which is not predominantly aimed at reducing the quantity of consumption but rather a change in quality. This aspect is often referred to as part of sustainable consumption. (v. Hauff 2014, p. 64)

Finally a structural change of available goods represents the third approach to reduce rebound effects. Here, a transition from material goods towards services and immaterial goods is pursued. Because the strategy of sufficiency is very diverse in its demands on individuals as well as on public policy, it is considered, mostly because of its lack of market-conformity, to be controversial. Moreover critics point out that the strategy of efficiency is able to solve environmental problems by technical advancement rendering the strategy of sufficiency irrelevant. As a matter of fact, the relevance of the strategy of sufficiency is difficult to communicate. Basically it postulates socially acceptable upper limits for economic growth in order to stay within the boundaries of the ecologic carrying capacity. The conception that a reduced consumption of resources does suffice for a contended life constitutes its basic idea. Therefore it strongly relies on the conviction of a large quantity of individuals and their willingness to implement a new paradigm for economic activity. (v. Hauff 2014, p. 64)

3.4 Resource Efficiency

The term resource efficiency describes the relation of a certain benefit or result with regard to the necessary resource input (Umweltbundesamt 2012, p. 23). In the context of this work, it refers to the application of raw materials and functional materials in the production of illuminants.

3.5 Energy Efficiency

Energy efficiency describes the ability of a system to efficiently convert energy into a desired functionality. The ratio of energy input to a certain use or result can be physically determined to create comparable quantities (Umweltbundesamt 2012, p. 7). For more specific information about energy efficiency in LED lighting see chapter "Quality Criteria for Solid-State Lighting".

3.6 Substitution

Faulstich (2010) states that criticality of resources can be mitigated by potential substitutes. The possibility to substitute a critical or vulnerable resource by a material featuring a minor supply risk is essential in reducing the impact of shortages of supply. However the close connection between the specific properties of raw materials and the technologies using them proves to be problematic. Since the chemical and physical properties of those materials facilitate the implementation of certain technological concepts in the first place, it is difficult to replace them. Thus the functionality of a device strongly depends on the availability of the respective raw materials. Additionally a successful substitution does not necessarily cause the intended saving of resources. The so-called rebound effect implies that an increase of resource efficiency, for example by substitution of critical or vulnerable raw materials, is overcompensated by elevated usage of the substitute. Reduction of costs and higher availability foster demand and consequently lead to an overall increase of resource demand. In this respect, it can be reasonable to research the application of innovative concepts instead of investing intense research and development with the aim to integrate new materials into existing technologies. Thus technological substitution, granted it does not lead to shortcomings in both functionality and quality, can contribute to reduction of the demand for critical materials. Since this process is part of general technological progress anyway, deliberate promotion of technological change is a worthwhile end. Moreover accelerated change towards technologies with lesser demand for critical raw materials reduces the requirements for associated recycling processes. Hence not only primary raw materials can be saved but also the winning of secondary materials ready to be reintroduced to the cycle of substances is facilitated. (Faulstich 2010, p. 43-52)

3.7 Recycling

Faulstich (2010) shows that systematic recovery of materials previously introduced to the value added chain is an essential measure to increase resource efficiency of economic circles and to minimize supply risks. Locations of high-tech industries like the European Union, which are strongly reliant on the import of functional raw materials, need the instrument of recycling to reduce dependencies and mitigate the impacts of possible shortfalls. Increasing the recycling quotas towards a more and more closed loop, recycling management not only saves resources but also reduces the aforementioned dependencies. In addition to the recovery of end-of-life materials, the maximized reintroduction of materials lost during production contributes to an economy of extensive reuse. Once raw materials enter the sphere of human technology and mobile or immobile deposits of functional materials are created, they become anthropogenic resources. Anthropogenic resources are all the materials, which have been extracted from the geosphere by humans. They comprise all matter which is incorporated in products and facilities, leaves the direct or indirect phase of production as waste or accumulates as deposits along the different stages of the economic circle of production. (Faulstich 2010, p. 22ff.)

Accordingly three categories of anthropogenic resources can be discerned in: "pre-consumer" waste, "post-consumer" waste (in English publications old scrap and new scrap respectively) and repository/landfill. Those terms originate from the German publication "r^3 - innovative Technologien für Ressourceneffizienz- Strategische Metalle und Mineralien-Informationspapier zum Forschungs- und Entwicklungsbedarf der gleichnamigen BMBF Fördermaßnahme"(Faulstich 2010).

Basically "pre-consumer" wastes are production-related scrap materials. They are usually very pure, not subjected to any aging and in continuous production. Due to those factors and the spatial concentration of the waste products the process of recovery is significantly alleviated. In contrast, "post-consumer" wastes contain materials that do not become available for recycling until the end of a product life cycle is reached. Also difficulties arise due to the fact that those wastes initially have to be collected, what necessitates logistic expense and adequate infrastructures. On grounds of their low grade purities and fluctuating concentrations, recovery processes become more complicated. Low purities and strongly varying concentrations also impede recovery from repositories and dumps. Those man-made deposits nonetheless constitute vast sources for secondary raw materials, which can be reclaimed by urban mining. The practice of urban mining also involves the recovery of discarded infrastructure, giving highly developed countries the chance to reincorporate functional materials into their supply chains. Among conventional building materials obsolete infrastructure includes valuable electro-technical installations, pipework, illuminants and electronic equipment. Those structures can represent valuable sources for rare or critical raw materials. (Faulstich 2010, p.24)

Considering the finite nature of resource deposits on our planet, the recovery of secondary raw materials has to be of primary interest. It gains even more importance if energetic savings in comparison to the production from primary resources are taken into account. Therefore recycling is one key aspect in reducing the emission of carbon dioxide and hence avoiding the further depletion of fossil fuels. Especially for metals, the transformation of resources to primary raw materials is very energy-intensive since they are mostly bound in chemically inert oxide compounds. This transformation is omitted for the case of secondary raw materials because energy-consuming production steps like initial processing and chemical reduction can be avoided. Moreover many production residues and waste types feature high concentrations of valuable or critical materials in comparison to geological deposits. Furthermore those material mixtures offer good accessibility once introduced to a value added chain. (Faulstich 2010, p.24)

With increasing priority of recycling operations an enhancement of existing procedures employed in recovery and processing becomes necessary. A large fraction of the waste produced in highly developed countries exhibit a high degree of complexity. Especially with regard to nondurable goods like toys, mobile phones and consumer electronics, low quantities of contained functional materials per device make it difficult to develop lucrative recycling concepts. Most recycling techniques are specialized in recovering basic metals like copper and steel from large bulks of scrap by melting. When complex electronic devices are introduced to such processes without previous selective dismantling and proper inspection most of the precious materials needed to provide their functionalities get lost. Thus new, innovative and cost effective methods of separation have to be developed in order to increase the capabilities of present day recycling. (Faulstich 2010, p. 25)

3.8 Criticality

Criticality is a concept that can be decisive for the future use of rare or functionally important materials. Giving a tool to determine the development of availabilities, it also provides information about the feasibility of certain technologies as well as the required supply chains (Reller et al. 2013, p.216-218). In summary, a raw material is rated as critical if it shows a comparably high risk to run into a shortfall of supply combined with an elevated economic relevance (see also European Commission 2014, p. 20). As Gantner (2016) describes, criticality assessment is a complex task involving many factors on global and regional scales. Not only the various qualitative and quantitative criteria, but also the lack of uniform definition of the term itself makes it difficult to issue comprehensive statements. Mostly the assessment of a respective material is strongly dependent on the context in which it is carried out. Many existing studies vary with respect to the considered timeframe, the weighing of the used criteria and the interests of involved stakeholders. (Gantner 2016, p. 29-40) A relevant study carried out by the European Commission (2010) for instance used core factors like geological availability, price development, social and ecological risks induced by mining, enterprise amalgamation, trade restrictions and technological progress to determine criticality.

According to Reller et al. (2013), geological availability of mineral resources in sufficient concentrations is crucial for the extraction of raw materials. Since the geological composition of the earth is extremely divergent, natural resources show an extremely heterogeneous distribution. Even if natural deposits show high concentrations, the technical feasibility of mining might not be granted or not profitable (Reller et al. 2013, p. 47). Also new mining projects may create new chains of supply with implications for existing processes as well as for the environment and the usage of other resources. In addition to that, geographical factors play an important role with regard to the availability of raw materials. Without the existence of suitable infrastructure and a proper socio-economic framework, winning of natural resources is difficult (Reller et al. 2013, p.216ff.). Moreover, the coproduction of other primary raw materials from the same deposit can determine the amount of by-products that become available for supply (Faulstich 2010, p. 4-5). Geological availability is not a fixed quantity but depends on the present knowledge of deposits around the globe. With only a portion of the planet's surface and most of all subsurface being completely explored, chances for the discovery of unknown deposits are still existent. Ongoing exploration of new mineral and ore deposits, the extension of existing ones and advances in mining technology often lead to an increase of the expected static range of natural resources (Reller at al. 2013, p. 92ff.). In this context, it is difficult to conduct long-term assessments. They can lead to wrong assumptions with regard to future developments of resource availability. Consequently, the considerations made in this thesis shall be restrained to short- to medium-term predictions.

As Gantner (2016) describes, the economic overall relevance of a particular raw material is also decisive for the outcome of large scale considerations. Some industry sectors heavily rely on materials that have little significance for others and vice versa. Keeping that in mind, it becomes necessary to make some generalizations so comparability on a larger scale can be achieved. By securing this comparability real context related importance of a functional material or a supply chain can be obliterated. Mostly "soft" or qualitative factors like the WGI (World Governance Index) and the HHI (Herfindahl-Hirschman-Index) can influence the outcome of an assessment if they are applied regardless of their actual deeper connection to the supply of a certain material. As far as ratings on a small scale are concerned, regarding a single company for instance, advisements can be far more precise and reflective in estimating the current situation of supply and demand. As a result the quality of a criticality assessment strongly depends on the framework within it is constructed. The usage of accurate data foundations (as far as they can be attained) and a precautious, adequate weighing of factors are of paramount importance. Hence a meaningful concept of criticality needs to be function-specific and context-related. This way a truthful depiction of circumstances can be granted and subsequently refined into concrete recommendations. (Gantner 2016, pp. 29ff.)

In addition to the aforementioned aspects that reflect a rather traditional respectively handed down perception of criticality, the introduction of the concept of functionalities can help to advance the expressiveness of future surveys on criticality. According to Gantner, adding the concept of functionalities leads to a revised understanding of the subject matter. Hence criticality can be defined as follows: "Criticality evaluates the availability of optional valorization of functionalities supplied by resources and/or raw materials on the basis of specific qualitative or quantitative criteria" (Gantner 2016, p. 40).

According the work of Gantner (2016) existing criticality assessments face some challenges in terms of methodology as well as consideration of functionalities. First of all, it has to be pointed out that most of the major surveys regarding criticality that have been carried out over the last years can be attributed to a small circle of authors. In an illustrative figure, Gantner (2016) shows the interdependencies that influenced the compilation of the most relevant papers or studies: repeated contributions of the same authors to different studies as well as the omnipresent adoption of methodological contents imply a stand-still in terms of expressiveness. It also becomes evident, that most studies build on the survey "Critical Raw Materials for the EU" conducted by the European Union. Further prominent studies have been conducted by the National Research Council (2008) and the U.S. Department of Energy (2011). This suggests the conclusion that the mentioned surveys methodically remain on the initial point of 2008 while mainly being subject to refinement on grounds of the rather symbolic asset of reputation. Furthermore the extensive omission of supply chains might be considered as a shortcoming. (Gantner 2016, pp. 7-8)

On the other hand one of the strengths featured by existing studies is comprehensibility as they provide their final assessments within clearly confined system boundaries. The materials considered are holistically evaluated according to selected criteria. Moreover concurrent comparisons between various raw materials can be drawn since every material is judged according to the same criteria. This approach grants the benefit of providing a good overview regarding all considered raw materials. Also qualitative and comparative assessment of all materials contained in the study is facilitated. Hence general problems can be identified without being distracted by overly detailed information. If the paper aims for deduction of recommendations for action or the presentation of options for action, strongly depends on the design of rating. (Gantner 2016, p. 40)

After all Gantner (2016) suggests that the most important surveys on criticality to date are strongly focused on the identification of supply risks instead of functionalities. Generally they succeed in delivering an outline on the current situation at the time of compilation. Furthermore the considered studies offer the possibility for comparison of multiple raw materials on a macro-level. The deduction of recommendations for action respectively options for action is however not pursued or not feasible at all. Based on the complexity of the topic, challenges like analysis of sub-problems, product- and functional relevance, geopolitical assessment, aggregation, weighing of indicators, lack of standards, lack of definition, neglect for supply chains and qualitative criteria, become evident. This creates the opportunity for the introduction of a revised concept of criticality. In acknowledging the fact that criticality has to be perceived in a way that includes its function specific and context-dependent character a new degree of significance can be achieved. (Gantner 2016, p. 40)

3.9 Functional Criticality and Critical Functional Materials

According to Gantner (2016) functionalities can be defined as material-specific properties, which are part of an operation, task or performance within an ongoing process or multiple ongoing processes. This process respectively those processes in turn are dependent on the specific properties of the used materials. In this connection it is important to note that a certain material is not necessarily restricted to one functionality, but can serve multiple purposes. Therefore material specific properties can fulfill their operation, task or performance on their own or as part of a larger process (Gantner 2016, p. 41).

In terms of (solid-state) lighting material specific properties are utilized to create functionalities embedded in a combination of processes that facilitate the generation of white light. For example gallium is used to fabricate semiconductor crystals that emit light when a suitable voltage is applied. In this form gallium contributes to the generation of light in its allocated functionality as part of a precisely manufactured solid state body. This structure, the LED die, is part of larger process represented by the creation of white light. Part of the emitted light is converted in a phosphor layer to manipulate the emission spectrum in such a way that the human eye perceives white light. The phosphor layer also utilizes the material specific properties of rare earth metals like europium to create the functionality of a chemical compound that serves as an efficient light converter. Only the interaction between those two functionalities incorporated into a larger process grants the main functionality of the device itself. This exemplifies the fact that material specific properties can be selectively allocated or functionalized. The intrinsic properties of a material can be changed depending on their chemical environment and the functionalities that have been allocated to them. Correspondingly the eventual active form into which a material is transferred decides over its actual properties. Hence functionalities describe the interdependency of material conditions with inherent properties as part of the processes in which they are involved.

As Gantner (2016) describes it is of great importance to recognize the relevance of functionalities when conducting a resource strategic assessment. Apart from their active forms, functionalities also exhibit different times of activity as well as various areas of activity. The acknowledgement of those spectra of activity is only feasible, if the underlying functionalities are taken into account. This necessitates a multidimensional approach in order to get an extensive grasp on all the aspects involved. Since criticality assessments are often closely related to industry, they should be orientated towards real supply chains. By establishing qualitative and quantitative criteria regarding functionalities as basis for criticality assessments, the evaluation of availabilities for those material specific functionalities in use becomes possible. Nevertheless functionality stays a term that cannot be conclusively defined or interpreted. (Gantner 2016, pp. 5-6)

Gantner (2016) further suggests that by incorporating the concept of functionalities into the context of criticality, the notion of criticality of functionalities can be deduced. Through conducting criticality assessments of resources on the basis of functionalities, supplemental options for evaluation become available. Due to the fact that up to now evaluations have mostly been executed on a macro-level, the assessment of functionalities offers more possibilities to make decisions or to derive alternatives for action. Therefore functionality-based criticality assessment can be understood as a problem- and practice-oriented form of criticality assessment. Its methodical advantages facilitate the evaluation of the specific vulnerability of distinct functionalities as well as of materials, raw materials and resources. As a result of context-specific detailed analysis executed on a micro-level it is possible to identify potentials, which unfold during use or valorization of the functionalities considered. In contrast to macro-level considerations, micro-level considerations allow for direct proactive reaction on supply risks in terms of risk prevention. (Gantner 2016, p. 41)

With respect to lighting technologies this function-specific adaption of the concept of criticality can be used to assess their potential for sustained application. As described before, modern lighting systems depend on specialized compositions of materials. Respective individual properties of raw materials are combined to form a compound with unique and most of all unsubstitutable functional properties. Accordingly this work defines substrates for crystal growth, epitaxial wafers, prefabricated LED chips for packaging and phosphors as functional materials (see chapter 5 and 6 for technical details). Their availability is coupled to undisrupted supply in the value added chain. If the fabrication of one of those materials is not able to keep up with the pace of the overall production process, the manufacturing of an illuminant cannot be completed. Hence aforementioned functional materials are regarded as critical components for persistent applicability of the illuminants containing them. It is to be noted that the described materials represent the best available solution with respect to the state of technology. Therefore substitution would result in functional impairments.

3.10 Significance and Limits of existing Conceptions

Criticality can be described in many ways. It has been the topic of many surveys over the last years with the goal to determine specific or overall supply risks for raw materials of elevated economic importance. Yet what most of these studies lack is an initial definition of the term itself to provide a prerequisite for the statements made. Mostly the term criticality is taken as a preexisting concept that does not require further introduction. Also despite the fact that criticality can be defined using various contextual connections and function-specific approaches, the reasons for the application of respective methods mostly stay elusive. Moreover, the basic approach to determine criticality has not changed much since the 1930s. In the past as well as today, the criticality of a raw material has been and is closely attached to its economic importance or rather the economic importance of its main applications and its risk of supply. (Gantner 2016, p. 2; Gandenberger et al. 2012, p. 45)

This suggests the conclusion that the advancement of the concept of criticality stalled since its first introduction in a military context in order to secure war supplies at the beginning of the First World War (in the scope of military considerations the term strategic materials has been established in analogy to critical materials as its civilian counterpart). As described by Gandenberger et al. (2012) mostly the thematic stagnation can be attributed to a strict focus on an unchanging set of indicators. Usually those indicators cover four main fields, which are represented by economic relevance, concentration of raw materials control, raw materials scarcity and social relevance. Since those categories also evoke non-quantifiable perceived criticality a generally binding definition of the terms critical or strategic cannot conclusively be established. (Gandenberger et al. 2012, p. 59)

As a result, in the aim to reach a high degree of significance, statements about criticality should be tailored to the framework in which they are being applied. Generalizations and inadequate factors that do not reflect the state of affairs are to be avoided. On the other hand, picking the right indicators for criticality with a raw material- and function specific focus leads to a more meaningful outcome. In the attempt to augment the concept of criticality to be more function-specific, the concept of functionality also has to be further elaborated. Within the perspective of resource strategy, functionality can be defined by a diverse and contextual set of aspects. Resources, raw materials, materials, applications, biological, ecological and economic functionalities can all be broached as issues when it comes to function-specific determinations of criticality. This necessitates a discussion of the term functionality in terms of content. The industrial sector is also beginning to acknowledge this need for considerations that are more far-reaching than the plain regard for supply risk and economic relevance. For instance the World Economic Forum emphasizes the principle of "Access-over-Ownership" in its report "Towards Circular Economy". This concept evaluates the use of functionalities higher than ownership of materials. (World Economic Forum 2014, p. 14)

4 Introduction to Solid-State Lighting

The following overview of the historic developments that led to LED lighting in its current form is based on technical literature published by Khanna (2014) and Liu and Luo (2011). Both publications give a comprehensive summary of the history of solid-state lighting. In addition, Haitz and Tsao (2010) provide scenarios of projected developments.

4.1 History of Solid-State Lighting

Since the early days of human culture the need for artificial lighting to prolong phases of economic or social activity was omnipresent. Over the course of history manifold sources of light were used. From simple campfires and torches over various forms of oil- and eventually gas lamps to the early stages of electric lighting, different principles of light generation marked the evolution of synthetic light. After the invention of limelight, the first nonelectrical solid-state lighting device in the early 19th century, the era of electrical illumination started and still endures. Initially simple patents like the Jablochkoff´s Candle (1880) applying the principle of arc discharge for the first time brought electric lighting to broader public attention. Nearly at the same time Joseph Wilson Swan developed a primal version of the incandescent lamp, a design further improved by Thomas Alva Edison, which revolutionized the way humans produced light. The incandescent light bulb was able to emit light without smoke, odor and fire hazard. The initial carbon filament was later replaced by filaments made of osmium, tungsten or tantalum causing for fundamentally improved durability. The introduction of the incandescent light bulb had ground-breaking implications for the development of industrial societies. Factories could be lit by night enabling production processes to be carried on around the clock. Also social activities could be extended into periods of darkness. Later the discovery of mercury- (1901) and sodium (1919) vapor lamps constituted an innovation, which laid the foundation for present day fluorescent lamps. In their wake also high pressure gas-discharge lamps followed, allowing for broader emission spectra and higher light output. Notable was the introduction of the first marketable fluorescent lamp in 1938 by the Westinghouse Electric Corporation, which had been deduced from an earlier German patent. It utilized phosphor based conversion of UV-light emitted by mercury vapor in a low-pressure discharge lamp. Further development of this lamp type included the introduction of antimony and manganese activated phosphors embedded in calcium halophosphate host structures. With the extensive use of incandescent lamps alongside fluorescent lamps in residential and industrial areas as well as sodium lamps in street lighting, a more compact form of the fluorescent lamp was introduced in order to save energy in domestic applications. The Compact Fluorescent Lamp (CFL) uses the same working principle like the previously mentioned fluorescent lamps but features smaller dimensions as well as a socket, which can be screwed into fixtures designed for conventional incandescent light bulbs. As breakthroughs on the field of solid-state lighting have been achieved, the light emitting diode emerged as a compact, efficient, dimmable and color adjustable light source, which is deemed to replace previous technological concepts. Its rise from a physical curiosity to indicator lamps and finally to high-performance lighting devices is described in the following lines. (Khanna 2014, pp. 6-8; Liu and Luo 2011, pp. 1-2)

As the British electrical engineer Captain Henry Joseph investigated the electrical properties of silicon carbide on grounds of its rectifying capabilities in 1907, he discovered a yellowish glow emanating from the material when a certain threshold of current was exceeded. Although the investigated device used a Schottky diode instead of a p-n junction it is considered to be the first light emitting diode. As the following decades did not exhibit new insights of relevance, the arrival of III-V compound semiconductors posed a vantage point for novel developments. Gallium arsenide, which could now be produced in the form of large crystals in the 1950s, was used to build infrared LEDs and lasers for the first time. Nick Holonyak Jr. further pursued the phenomenon of electroluminescence in his studies at the General Electric Company as he developed the first visible spectrum LED using a III-V compound semiconductor in 1962. Gallium arsenide phosphide (GaAsP) proved to be a suitable material as it is still used to build indicator lights and simple forms of displays. Since then lasers and LEDs based on III-V compound semiconductors became subject of continuous development. Despite the increased focus on laser diodes, new materials emitting in various colors except blue were discovered in the time after Holonyak´s discovery. Green nitrogen doped gallium phosphide LEDs were commercialized in the following years. With the introduction of a new material system consisting of aluminum gallium arsenide (AlGaAs), which featured a direct bandgap, remarkable improvements in terms of luminous efficiency were achieved. Also the new material was accompanied by innovations like a fully lattice-matched heterostructure grown on GaAs or even on transparent AlGaAs substrates respectively. In the 1990s the aim to produce red and blue lasers led to the discovery of novel systems like InGaP/GaAs and eventually GaInAlN/GaN. At this time fundamental advances in epitaxial growth methods paved the way for the introduction of new compositions. By employing organometallic vapor-phase epitaxy (OMVPE) high-brightness LEDs made of AlInGaP in colors ranging from yellow to red could be produced. Those advances also facilitated the production of amber to red colored aluminum indium gallium phosphide (AlInGaP) diodes. After further refinement of production techniques eliminated problems like structural shortcomings, acceptor passivation and aluminum oxidation, novel AlInGaP LEDs could be endowed with very high quantum efficiencies. (Khanna 2014, p. 8-16; Liu and Luo 2011, p. 2-4)

The next steps of evolution took place on the field of light utilization. Although remarkable progress concerning the performance of the actual LED die were made, most of the emitted light did not reach the outside. Techniques like the incorporation of Bragg reflectors into the dies and the removal of light absorbing substrates had large impacts on outcoupling-efficiencies as well as improved packaging and optics. However, due to their limited light output, the aforementioned technologies were still limited to display and signal applications like outdoor signs or automotive stoplights. With the following practical utilization of nitride based LED dies a fundamental breakthrough in solid-state lighting technology was achieved. Because of its bandgap characteristics, AlInGaN allows for the emission of light ranging from the green to the ultraviolet portion of the spectrum. The Japanese scientists Shuji Nakamura, Isamu Akasaki and Hiroshi Amano were the first to master the complex challenges connected with the growth of nitride based semiconductors. Hence it was possible to fabricate full color LED signs on the basis of the three primary colors for the first time. The availability of blue LEDs also initiated the revolution in lighting technology that can be witnessed today. In combining the emission of blue light with a down-converting layer of yellow phosphor, Nakamura was able to develop the first white LED in 1996. Since then, various efforts of optimization resulted in the introduction of the first commercial high-performance white LED by Lumileds Lighting only two years later. Those devices now operated at power levels 1000 times higher than those of their indicator lamp ancestors. In addition the success of modern day LEDs was ushered by miniaturization of package size, a substantial increase in thermal resistance and high overall longevity. Since then more refinements regarding the doping process of semiconductor structures and material compositions led to a wide range of available colors as well as infrared and ultraviolet wavelengths. (Khanna 2014, pp. 209ff.; Schubert 2006, pp. 1-22; Liu and Luo 2011, pp. 6-10)

4.2 Recent and future Developments in Solid-State Lighting Technology

In his book "Fundamentals of Solid-State Lighting" Khanna (2014) also gives a detailed summary of the projected developments in solid-state lighting. His statements augment the remarks of Haitz and Tsao (2010) in their publication "Solid State Lighting: 'The case' 10 years after and future prospects". Both publications provide the informational basis for this section.

Light emitting diodes for general illumination have nowadays reached properties that make them competitive if not superior to other light sources. Still, the potential offered by solid-state lighting has not yet been exhausted. New infrastructure and methods of production are bound to make LED-lighting more affordable. Moreover the quest for increased luminous efficiency is eagerly continued. Peak efficacies for packaged LED devices are expected to reach approximately 250 lm/W by 2020. Depending on the desired color temperature and color rendering index and most of all due to losses caused by the incorporation into luminaires, 200 lm/W is expected to be a first rate value for high performance devices. This corresponds to efficiencies 15 times higher than that of an incandescent light bulb. Alongside the continuous refinement of LED technology, organic light emitting diodes (OLEDs) are deemed to gain relevance in the near future. On account of their diffuse and planar manner of light emission OLEDs are suited to complement the spotlight-like directional character of their inorganic counterparts. Limited by challenges like stability, cost, longevity and manufacturability organic light emitting diodes are yet to reach the stage of extensive marketability. Until then the LED will strengthen its lead by aforementioned technical advancements and most importantly by competitive pricing. (Khanna 2014, pp. 491-501)

Haitz and Tsao (2010) predict that even though prices are expected to significantly drop towards the year 2020, lighting systems like retrofit Edison-socket incandescent and compact fluorescent lamps will still constitute a major share of the market in many parts of the world. As far as future spread of LED-lighting is concerned, governments of developed nations are anticipated to promote solid-state lighting due to its high efficiency and lack of toxic substances. In this scenario, it is the mercury-content of fluorescent lamps that will eventually lead to a cut in subsidies resulting in the loss of competitive edge for this technology. In the projected switch to LED lamps for business and residential use, infrastructural decisions become necessary. Since the use of light emitting diodes requires different electrical supply than conventional light sources, two possible solutions do compete. On one hand, current wiring equipped to supply medium-voltage AC power has to be adapted by attached converters to provide a form of power, which is suitable to operate LEDs. Such devices create losses and add complexity as well as increased resource input to LED luminaires. Additionally flicker may be observed when LEDs are operated on AC power lines what can cause health problems or discomfort. On the other hand, the introduction of low-voltage DC power for electrical lines intended for illumination poses a structural challenge in terms of integration into the persisting grid structure. During the course of new building efforts or the refitting of existing buildings, the decision for the last-mentioned solution features advantages like low-lifetime system cost, high efficiency and increased degree of system integration. However due to added complexity and cost, private home owners and enterprises might shy away from investing into a second lighting specific wiring of their structures. Aside from challenges regarding fixtures and power supply there are still some technological issues that have to be addressed in the coming years. (Haitz and Tsao 2010)

The prevention of droop for example is of high interest concerning its effect on power consumption and both the associated economic and ecologic implications. The drooping effect describes the considerable decrease in device efficiency upon raising the operational forward current applied to an LED. The reasons for this effect are not extensively elucidated and necessitate further research. Furthermore the development of advanced gallium arsenide substrates for crystal growth is an important aspect in raising the internal quantum efficiencies of LED dies. With the use of novel substrates, quantum physical effects, which negatively affect the recombination of electrons and holes in the active layers of LEDs can be mitigated. Mostly those effects are caused by lattice mismatch between the substrate and the desired crystal structure of the LED itself. Another field for possible improvement is phosphors. With the use of narrow-band red phosphors, efficiency losses caused by broad spectral distribution of conventional phosphors can be lessened. Innovative phosphor materials also contribute to better color rendering indices and more pleasant light tones. As conversion efficiency of phosphors suffers considerably from elevated temperatures, their adequate incorporation into LED luminaires and the prevention of heating are matters of interest too. New designs include the use of ceramic binding materials in order to enhance heat flux and temperature stability. Phosphor related problems can also be avoided by the development of more efficient green LEDs. Advanced fabrication techniques for InGaN dies are able to reduce efficiency deficits of green LEDs in comparison to red and blue ones. This way a red-green-blue multi-color approach becomes easier to facilitate, rendering phosphors and the associated losses in light conversion unnecessary. Since LEDs represent small spot-like sources of light, the distribution of light is to be altered to a more uniform pattern for some applications. By developing special plastic lenses that are able to disperse the emitted light with minimal losses in output another advantage in functional variety can be added to the solid-state lighting portfolio. Furthermore the introduction of intelligent lighting systems can lead to new levels of efficiency and comfort. Intelligent controls sense ambient lighting conditions as well as occupancy and react by switching and dimming of installed LED luminaires. Finally the formulation of new standards for lighting devices is an important aspect in the aim to create comparability for different lighting technologies. Uniform standards and test protocols help to relieve confusion when it comes to comparing diverse products and their classifications. (Khanna 2014, chapter 492ff.; Haitz and Tsao 2010)

Concerning the future development of solid-state lighting beyond the year 2020 the predictions of Haitz and Tsao (2010) are reproduced in the following:

Dr. Roland Haitz, a late distinguished researcher on the field of LED technology, is the author of Haitz´s law which, in analogy to Moore´s law for silicone semiconductors, projects the development of LED technology. In accordance with Moore´s law that predicts the number of transistors in a chip to double every 18 to 24 months, the luminous flux of an LED is also to double every 18 to 24 months (Khanna 2014, p. 11). His former colleague Jeffrey Y. Tsao, also a renowned researcher, is currently working at Sandia National Laboratories. He is engaged in integrated science and economic modeling for solid-state lighting (see Tsao, biographical details).

Together they published two much-noted consecutive papers on the future developments in solid-state lighting. The first paper, which was published in 2000 made empirically based predictions that helped to spark investments into an emerging disruptive technology. In 2011 they issued a revised and updated version that includes the aforementioned contemporary developments and arising technological challenges. (Haitz and Tsao 2010) This publication is subdivided in projections for the time-period 2010-2020 and the following time representing the time after 2020. As far as the stage of development in the year 2020 is concerned, Haitz and Tsao (2010) make their predictions on the assumption of continuous and extensive government and industry funding for research. According to them, high quality LED lamps will reach luminous efficacies in the range of 150-180 lm/W surpassing traditional light sources by factors of 2x to 10x. Also the OEM price for cool white lamps is to decrease to $0.6/klm leading to a revolution of the lighting market on grounds of performance advantages and affordability. The branch of industry responsible for the production of display backlighting is expected to have significant influence on price and performance development due to massive investments in production infrastructure. Therefore a period of overcapacity will coincide with a phase of rapidly increasing demand resulting in further price deterioration. Those processes are to be supported by a shift of government incentives from CFLs to LEDs by reason of efficiency drawbacks, difficult waste disposal and hazardous mercury content. For the time beyond 2020 the authors make their own respective assumptions.

Haitz argues that LED technology itself will come to a point where further improvements become incremental and require for large expenditures. Therefore, at this point of partial stagnation, the price of LED lamps will be governed by other factors like cost of metals, distribution, government mandates or plastic materials. By the end of the next decade, the OEM cost of light is to drop below $0.5 per klm and non-technical reasons such as lighting taxes to prevent the excessive use of illumination products will represent the main cost factors. Moreover more practical and user-friendly low- to medium- flux products will dominate the market aside from few prestigious ultra-high performance packages for special applications. Tsao however is of the opinion that efficiency figures will keep increasing until values saturate at a level of about 250-300 lm/W. He gives three reasons to support his predictions. First the investment cost for LEDs will drop below a price that renders the operational cost of the luminaire the decisive factor. Therefore consumers are expected to willingly spent money on more efficient solutions in order to reduce energy costs in a reasonably period of amortization. Second improvements in packaging and the associated cost savings in production will result in increased efficacy and the emission of less waste heat. Third the versatility of solid-state lighting will allow for the integration of additional features supplemental to the plain production of synthetic light. Considering the vast functional and integrational possibilities of semiconductor technology, functions like the digital tuning of chromaticity and temporal or spatial distribution of light respectively are expected to represent considerable augmentations. Also the introduction of those features will boost the development of shallow red emission phosphors helping to raise efficiencies by the reduction of Stokes shift. (Haitz and Tsao 2010)

Despite the conjectures about the bright future of solid-state lighting it is important not to forget that those devices produce light for humans. Hence the key for a successful replacement of conventional lighting systems is the compliance with human needs and perceptions. LEDs have made remarkable progress evolving from small indicator lamps to traffic signals and flashlights and finally to serious sources of light for residential and commercial purposes. But still in addition to their potential high-grade efficiencies of about 70%, shortcomings in color rendering and light temperature pose the last hurdles for the ascension to be the dominant source of general lighting. Also in addition to improvements on the field of light characteristics for LEDs, the organic light emitting diode (OLED) is expected to fundamentally increase in efficiency. Henceforth becoming suitable for advanced ambient light applications where entire walls and ceilings turn into lighting systems themselves. All in all it is highly important to follow technical developments and to keep pace with technological progress in order to utilize the potential of solid-state lighting. Training professionals to reach a high degree of insight into novel developments and the associated opportunities, market adoption of solid-state lighting can be further promoted. This way potential challenges and chances can be identified more quickly making LED lighting more competitive in a shorter period of time. (Khanna 2014, pp. 491-501)

5 Theoretical Background of LED Technology

The following chapter features explanations about the physical working principles of light-emitting diodes and phosphors. The used information was taken from technical literature published by Khanh et al. (2015), Khanna (2014), Liu and Luo (2011) and Schubert (2006).

5.1 Physical Principles of Light-Emitting Diodes

Light emitting diodes found their way into all kinds of everyday applications, yet their functional principles remain elusive for most people. By using semiconductor crystals to emit light under the application of electrical currents, the physics of light generation fundamentally differ from conventional concepts like the classic light bulb or fluorescent lamps. In contrast to Planckian radiators or gas discharge lamps respectively, LEDs exhibit a phenomenon called injection electroluminescence. By making use of transitions from electronic states with high energy to electronic states with low energy in a solid-state body, electromagnetic waves can be extracted. Most important for this process to occur is the existence of a carrier depleted region at the interface of one positively doped and one negatively doped semiconductor. This so called p-n junction is characterized by an abrupt transition between two differently doped semiconductor materials, but also requires well matched atomic layers to perform properly. In doping semiconductors their electrical properties can be systematically manipulated to enhance conductivity and tune their polarity. In this respect, n-type doping means the deliberate enrichment of semiconductor materials with atoms of higher atomic order to add additional electrons to their conduction band, thus creating more negative charge carriers in the solid. In contrast, p-type doping with atoms of lower atomic order will create more positive charge carriers (holes) in the valence band of the material. For example by joining one positively- and one negatively doped portion of the same material in a preferably abrupt junction, while preserving the periodicity of the crystal lattice, a suitable structure to obtain light emission can be fabricated. In this structure, which is called a homojunction, the majority carriers of the respective materials diffuse to the side with opposed polarity forming a depletion region. The consequently emerging electric field exerted by ionized donors and acceptors spanning the junction area finally becomes strong enough to prevent the depletion region from further extension. (Khanh et al. 2015, p. 49ff.; Khanna 2014, p. 67ff.; Schubert 2006, p. 59ff.)

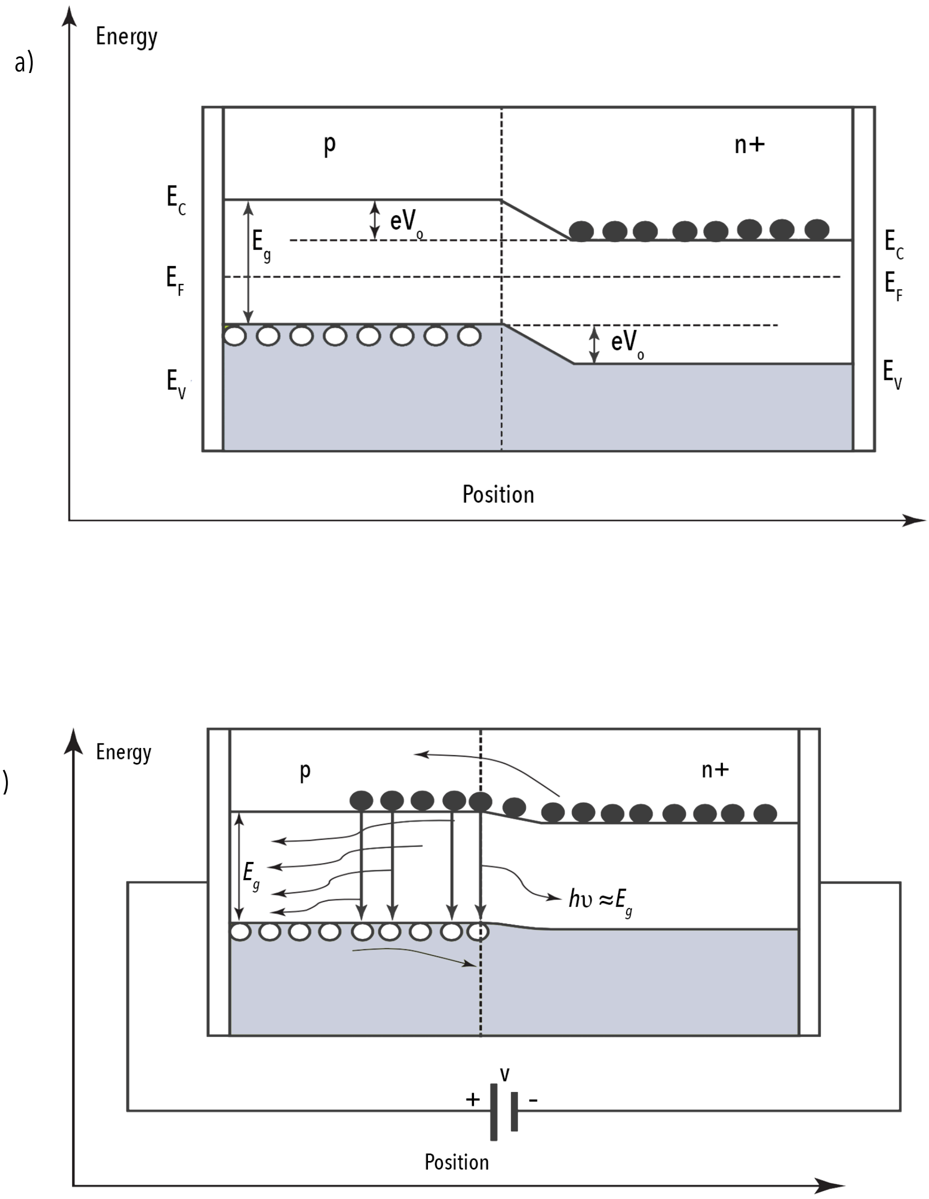


Fig. 2: Working principle of a p-n homojunction

a) Energy diagram of an idealized p-n junction in equilibrium state.

b) Energy diagram of an idealized p-n junction with applied forward current

Here E_C is the energy of the conduction band, E_F is the fermi energy, E_V is the energy of the valence band, E_g is the band gap between the valence band and the conduction band and eV_0 is the magnitude of the energy barrier caused by the built in voltage V_0. (Khanh et al. 2015)

Due to the fact that the subsequent formation of a potential barrier only allows electrical current to flow in one direction under a certain threshold, the structure works as a diode. With the application of a suitable forward voltage minority carriers will be injected into the depletion region allowing them to recombine and emit light. The wavelength of this light emission is determined by the bandgap of the deployed semiconductor. Furthermore one decisive aspect is the need for direct bandgap semiconductor materials in order to get significant light emission (The reader is referred to any textbook on quantum physics for more information about energy-band diagrams and the band model). (Khanna 2014, pp. 69-90)

Different materials and most of all, different material compositions, as explained in the following section, make for diverse emission characteristics. Nonetheless, what all light emitting diodes have in common, are their fairly monochromatic emission spectra. Based on the nature of the conduction and valence bands of the respective material the linewidth of the emission is more or less narrow. Still, the linewidth is very small in comparison to the scope of the whole visible spectrum. Hence the human eye cannot draw a distinction and the LED appears to be monochromatic. (Schubert 2006, pp. 89-90.)

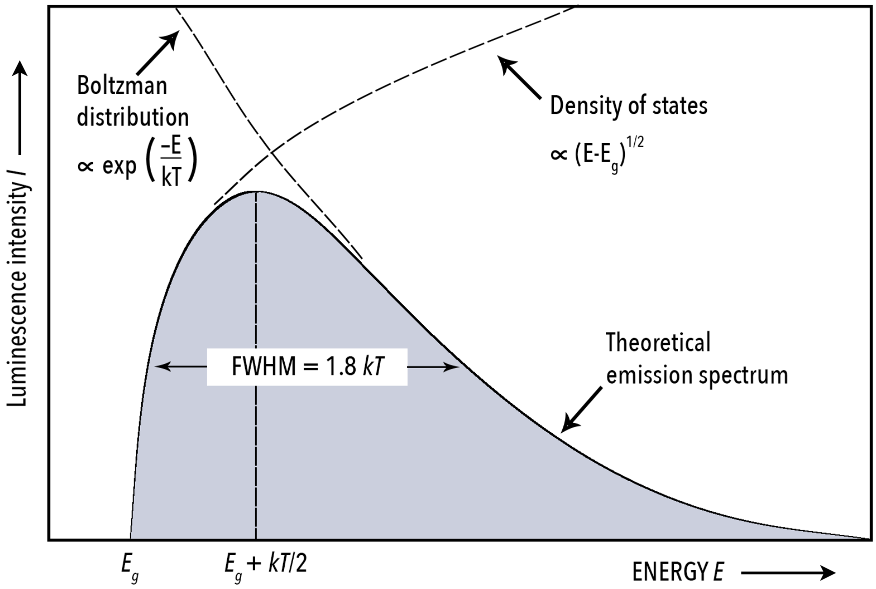


Fig 3: Full-width at half-maximum of an exemplary light-emitting diode. For this instance the full-width at half-maximum (FWHM) of the emission curve is 1.8 kT (Schubert 2006). The (FWHM) is an important measure for light quality. It provides information about the purity of the emission color. It is determined by the width of the intensity curve at 50% of the total spectral power or emission intensity. Smaller values correspond to higher degrees of monochromaticity in LEDs. A small FWHM is desirable in cases where phosphors with rather narrow excitation spectra are used to convert the emitted light. (Schubert 2006)

Even when a p-n junction is capable of light emission, it still suffers from the competition between radiative and non-radiative recombination. The relative intensities of those two mechanisms determine, whether an LED shows the ability to transform electric current into emitted light effectively. In contrast to former where a photon is emitted with an energy corresponding to the bandgap of the material, the latter means a conversion of the potential energy of the electron transition into vibrations of the surrounding crystal lattice. In this way the afforded energy originally intended to cause light emission is lost in heating the bulk semiconductor material. Moreover excessive heating will impair the probability of radiative recombination. Fig. 4 below shows the functional principle as well as a simplified energy-band diagram of a homojunction, which is the centerpiece of a basic light emitting diode. (Schubert 2006, pp. 27-45)

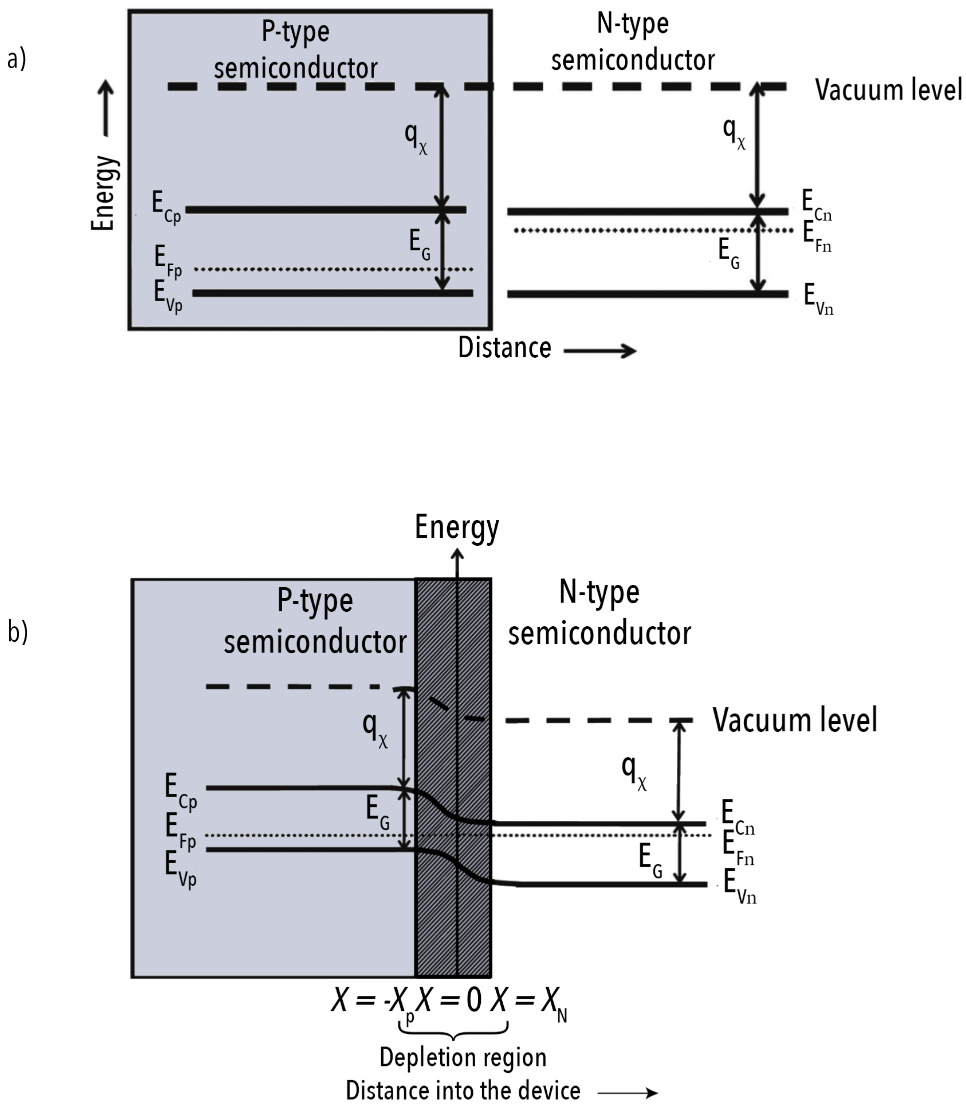


Fig. 4: Energy-bands and depletion region in a p-n homojunction I.

a) Schematic depiction of the electronic band structure in a p-type and n-type semiconductor before contact.

b) Schematic depiction of the electronic band structure after contact and subsequent formation of the depletion region. (Khanna 2014)

Homojunctions consisting of a single p-n junction were the first structures to be used in simple light emitting diodes for indicator lamps or calculator displays. Due to poor current injection properties and insufficient carrier confinement, those structures have been replaced by the more refined heterostructures or even very sophisticated multi quantum well structures. Those not even feature materials of differing doping but also different materials with unequal band gaps in precise metallurgical junctions. (Schubert 2006, p. 1-22)

In terms of electrical properties of light emitting semiconductor diodes, there are some basic principles that have to be considered. Owing to the different Fermi energies of n-type and p-type semiconductors, unique characteristics form at their interface. By bringing them in contact, the majority carriers of one side will diffuse into the other side and vice versa. This majority-carrier diffusion current will be balanced out by an opposed electrical field caused by the stationary donor and acceptor ions. The resulting space charge region induces an opposed minority-carrier drift current that lies in equilibrium with the diffusion current. Based on those material dependent currents the width of the depletion zone can be calculated:

$$W_D = \sqrt{\frac{2\varepsilon}{e}(V_D - V)(\frac{1}{N_A} + \frac{1}{N_D})} \tag{5.1}$$

, where N_A is the acceptor concentration, N_D is the donor concentration, V_D is the diffusion voltage, V is the diode bias voltage and $\varepsilon = \varepsilon_r \varepsilon_0$ is the dielectric permittivity of a semiconductor.

If a current is applied to this dynamic equilibrium, electrons and holes are injected into the depletion layer. There, they recombine under the emission of light and an overall current flow across the junction can be observed. The current-voltage characteristic of a p-n homojunction is described by the Shockley equation,

$$I = eA(\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_A})(e^{\frac{eV}{kT}} - 1) \tag{5.2}$$

where $D_{n,p}$ are the electron and hole diffusion constants respectively, $\tau_{n,p}$ are the electron and hole minority carrier lifetimes respectively and n_i represents the intrinsic carrier concentration of the semiconductor.

With the application of a reverse bias, the current through the diode saturates a material specific value and can only be increased by the impression of very high voltages that lead to a breakdown and hence destruction of the diode. (Schubert 2006, pp. 60-61; Khanna 2014, pp. 93-111)

The I-V characteristics for the application of a reverse bias and the saturation current I_s are shown below:

$$I = I_s(e^{\frac{eV}{kT}} - 1) \quad with \quad I_s = eA(\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_A}) \tag{5.3}$$

The I-V characteristics for typical forward bias conditions can be represented by an adapted form of the Schockley equation because of *V >>kT / e* and therefore [exp (*eV / kT)* -1] ≈ exp (*eV / kT*):

$$I = eA(\sqrt{\frac{D_p}{\tau_p}}N_A + \sqrt{\frac{D_n}{\tau_n}}N_D)e^{\frac{e(V-V_D)}{kT}} \tag{5.4}$$

This effect is caused by the externally aided further increase of the built-in potential widening the depletion region at the interface. The Fermi Level on the p-side is raised and on the n-side lowered respectively leading to an increase of the barrier height by the magnitude of the reverse bias.

$$I_{n0} = \frac{qD_n n_i^2 A}{L_n N_A} \tag{5.5}$$

This way diffusion across the junction is prohibited. With increasing width of the depletion region, also the intrinsic drift current of minority carriers increases to a certain extent. (Khanna 2014, p. 97)

If a power supply is connected to the junction in a forward biased manner that acts in opposite direction of the built-in potential, significant current flow occurs over a certain threshold voltage. In contrast to the case of reverse bias, the barrier height to diffusion current is reduced and the overall current begins to rise in the regime of the diffusion current component. Under forward bias, the Fermi levels of the respective sides of the p-n junction experience an adaption according to the amount of applied external voltage V. Also a band-bending takes place, which reduces the difference in energy of the valence and conduction bands by the magnitude of the external voltage. As a result the diffusion current increases by the ratio (qV/k_bT) while the barrier for diffusion currents is simultaneously diminished. This way, the migration of majority carriers to regions of opposite doping is eased. Those injected carriers then recombine in a radiative or nonradiative manner resulting in either the emission of light or the translation to lattice vibrations respectively. The total diode current is

$$I = (I_{p0} + I_{n0})[(exp\frac{q(V - IR_s)}{k_B T}) - 1] + I_{nrad0}[(exp\frac{q(V - IR_s)}{\zeta k_B T}) - 1] \tag{5.6}$$

where ζ is the ideality factor ($1 \leq \zeta \leq 2$), I_{nrad0} is the nonradiative current, R_s is the series resistance of the multi-layered LED, I_n is the electron current under forward bias and I_p is the hole current under forward bias.

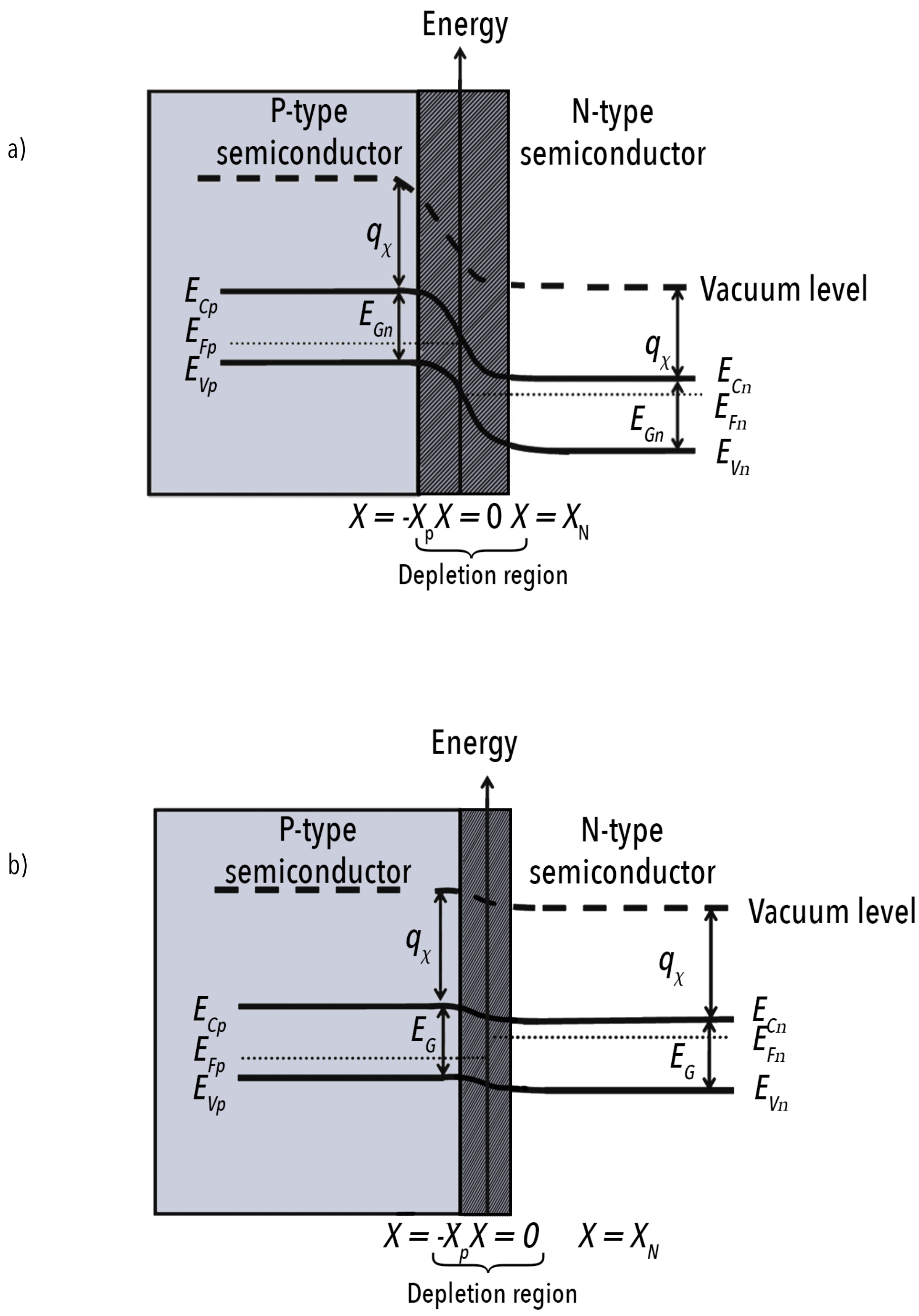


Fig. 5: Energy-bands and depletion region in a p-n homojunction II.

a) Schematic depiction of the electronic band structure in a p-n homojunction with applied reverse bias.

b) Schematic depiction of the electronic band structure in a p-n homojunction under applied forward bias. Both show the respective variations in depletion layer width. (Khanna 2014)

The efficiency of the emission of light strongly depends on the injection efficiency of the junction in use. In order to maximize it, asymmetric profiles are employed which relocate the area of recombination either into the p- or n-region away from the depletion zone. By heavily doping one side of the junction in relation to the other, this displacement of the active region can be achieved. Yet heavy unbalanced doping shows disadvantages that are discussed in the following section. (Khanna 2014, pp. 106-110)

In an attempt to further increase injection efficiency and to overcome the shortcomings of asymmetrically doped homojunctions, the heterojunction has been developed. Mostly, disadvantages arise from the high defect densities as a consequence of heavy doping. Those impurity complexes serve as centers for nonradiative recombination and hence cause reduced light output. Moreover reabsorption processes in the surrounding materials also play an important role in decreasing the light actually leaving the crystal to be used for illumination. Unlike the aforementioned homojunction, a heterojunction consists of two different materials with nearly identical lattice constants but differing band gaps. Intricate metallurgical processes to manufacture those structures provided by bandgap engineering are used in order to avoid defects caused by lattice mismatch or defect formation at the interface. (Khanna 2014, pp. 113-114)

In a light emitting diode, the efficiency of recombination is governed by the mean diffusion length of minority carriers. When a carrier is injected into an area of opposite doping it will eventually recombine. The diffusion length describes the mean distance an electron or hole travels as a minority carrier before it recombines:

$$L_n = \sqrt{D_n \tau_n} \tag{5.7}$$

$$L_p = \sqrt{D_p \tau_p} \tag{5.8}$$

Due to the fact that typical diffusion lengths are of the magnitude of several micrometers, the minority carriers are smeared out over a large region across the junction. Thus the concentration of minority carriers in the active region is relatively low. This accounts for a low rate of recombination as well as extends the recombination lifetime. Heterostructures cope with this problem by confining the carriers to a narrow area around the active region. (Schubert 2006, pp. 69ff.)

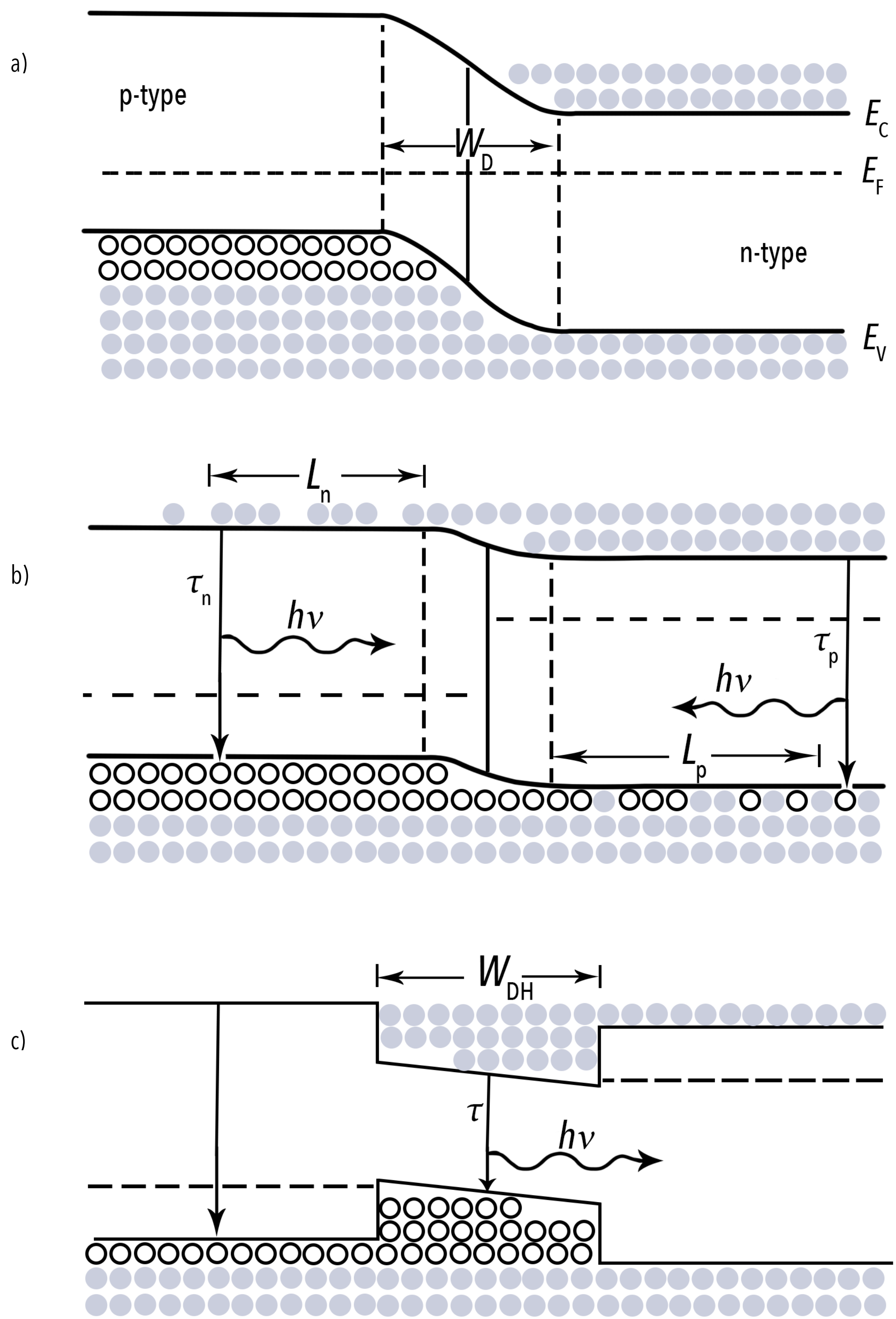


Fig. 6: Comparison between carrier distributions in a p-n homostructure and a p-n heterostructure.

a) P-n homojunction with no voltage applied

b) P-n homojunction under forward bias

c) P-n heterojunction with applied forward bias

Average diffusion lengths of minority charge carriers across a homojunction before recombination are L_n and L_p respectively. Heterojunctions in contrast show a confinement of carriers by the built-in heterojunction barriers. (Schubert 2006)

By introducing two regions of larger bandgaps to outline the active region, barriers are created, which confines it to a width of 0.01 to 1.0 μm. This two-sided confinement structure is called a double heterostructure. Consequently the region in which the carriers recombine is governed by the width of the active region and not by the diffusion length. In addition to increasing the radiative recombination rate, heterostructures offer the advantage of very precisely located active regions and therefore packaging that enables high extraction efficiencies. Furthermore light extraction out of the device is augmented by the fact that light emitted in the active region is not absorbed while passing through the large-bandgap layers (Khanna 2014, p. 120). Apart from their obvious benefits, heterostructures feature some problems that have to be dealt with accordingly. First, heterojunctions show increased electrical resistance at their interfaces. Due to the formation of an electrostatic dipole at the boundary between the large-bandgap material and the small-bandgap material, electrons passing through the structure have to overcome a now built-in barrier by either tunneling or thermal emission. This effect is caused by the diffusion of electrons from the large-bandgap material over to the small-bandgap material occupying conduction band states of lower energy. As a consequence, a positively charged depletion layer with ionized donors in the large-bandgap material as well as a negatively charged electron accumulation layer in the small-bandgap material do form. (Schubert 2006, pp. 70ff.)

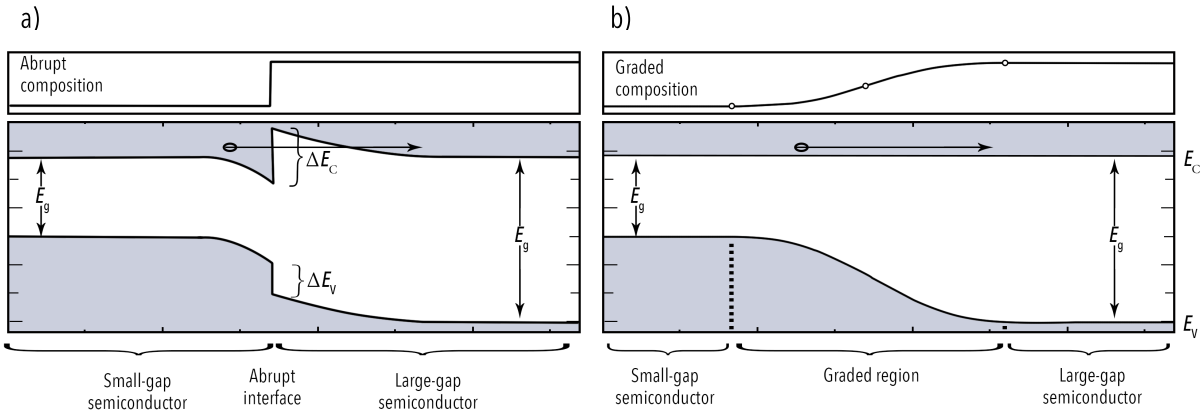


Fig. 7: Graded composition doping of materials with different band gaps.

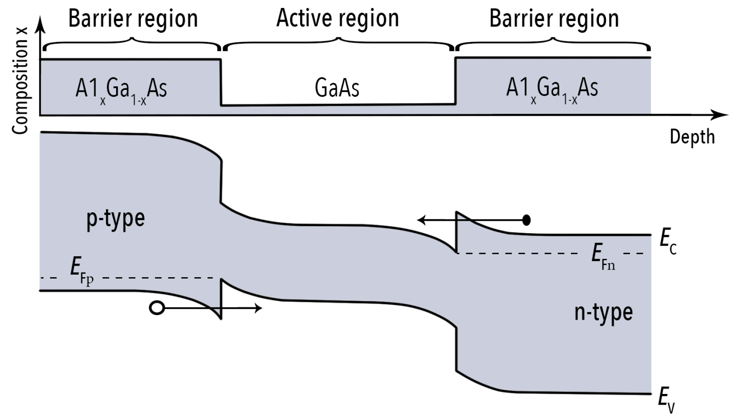
a) Band structure of an n-type-n-type heterojunction with abrupt transitions.

b) Band structure of a graded transition between two semiconductors with different band gaps.

Former showing a higher electric resistivity due to the formation of an electron barrier at the abrupt junction (ΔE_C and ΔE_V). (Schubert 2006)

These additional resistances produced by heterojunctions are be detrimental to the performance of LED-chips. Moreover, high-power devices suffer from the heat dissipated by the heterostructure resistance and consequently lose radiative efficiency due to heating of the active region. Nonetheless, those band discontinuities can be completely prevented by grading of the chemical composition of the semiconductor materials adjacent to the heterostructure. As it appears in the above-shown figure, there are no peaks in the conduction band left to restrain electron flow. Especially material transitions with parabolic concentration gradients show resistances comparable to those of bulk materials. The reason why a parabolic gradient is preferable lies in the fact that the electrostatic potential also has a parabolic shape and therefore a parabolic variation of material-composition compensates for the parabolic shape of the depletion potential. (Schubert 2006, pp. 70ff.)

a)



b)

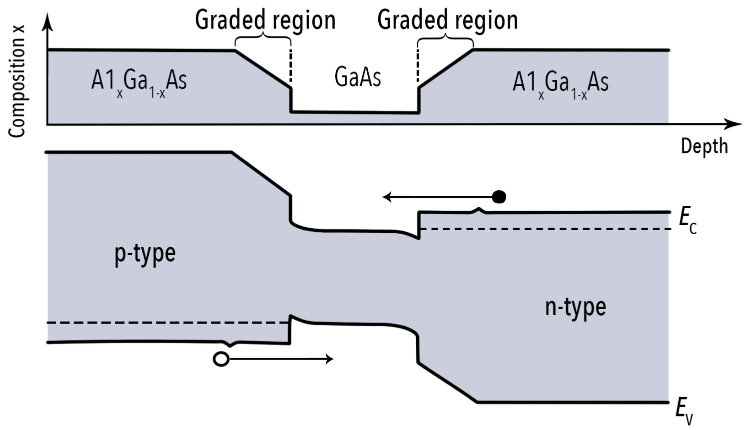


Fig. 8: Graded composition doping in double heterostructures.

a) Band structure of a double heterostructure with abrupt junctions.

b) Band structure of a double heterostructure with graded junctions.

Former shows a higher electrical resistivity than the graded transitions in the second example. The reason for this effect is the formation of electron barriers at the interfaces of the respective layers. (Schubert 2006)

Another problem that heterostructures face is carrier loss. Some carriers that should be confined to the active region in an ideal structure can nevertheless escape their confining barriers and relocate to the adjoining large-bandgap layers. Owing to their Fermi-Dirac-like distribution in the active region some carriers have enough energy to overcome the confining barrier and escape to the barrier region. The carrier concentration in these areas is rather low and thus recombination occurs with low radiative efficiency. (Schubert 2006, pp. 69ff.)

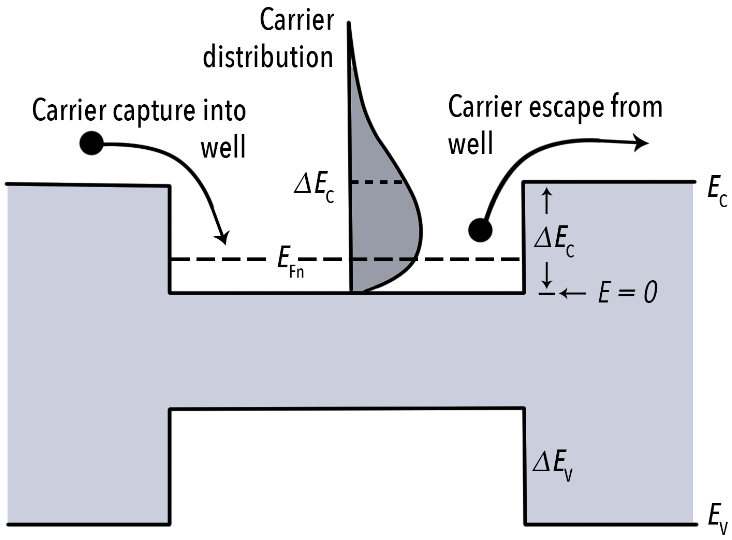


Fig. 9: Schematic diagram of carrier capture and escape in a double heterostructure. Additionally the distribution of carriers inside the active layer is shown. (Schubert 2006)

This leakage current is also dependent on the carrier concentration at the edge of the barrier. Hence barriers are required to exceed the thermal energy kT by as much as possible to ensure effective confinement even for the case of device heating.

Another effect impairing the radiative efficiency of heterostructures is the overflow of carriers. At high injection currents the Fermi energy in the active region is raised by increase of carrier concentration. With high enough currents carriers become abundant in the active region and overflow the barriers imposed by the confinement layers. As a result, further increase of the externally applied forward voltage does not generate any additional light emission.

As the preceding remarks show, carrier confinement is essential to the efficient emission of light in semiconductor devices. By replacing heterostructures with structures that feature even better confinement properties higher efficiencies can be achieved. Most important in this respect are electron blocking layers and quantum well heterostructures. Electron blocking layers are an effective way to deal with carrier leakage across the interface between the active- and confinement regions. Those electron blockers consist of materials with high bandgap energies and are incorporated into the structure as a further layer between the aforementioned regions. (Schubert 2006, pp. 75-81)

Quantum wells (QWs) basically are confinement regions significantly smaller in width than conventional heterostructures and therefore further increase carrier concentration. In a quantum well the motion of electrons is restricted to a direction perpendicular to the crystal growth. Potential energies within the well layer are lower than in the surrounding layers leading to a quantization of the motion of electrons across it. Accordingly electrons and holes will get caught in this region of lower energy and accumulate in a very dense manner. As the name quantum well implies, such a structure can be seen in analogy with a potential well or, more simplified, with an actual well requiring energy for objects to leave again if once entered from the topside.

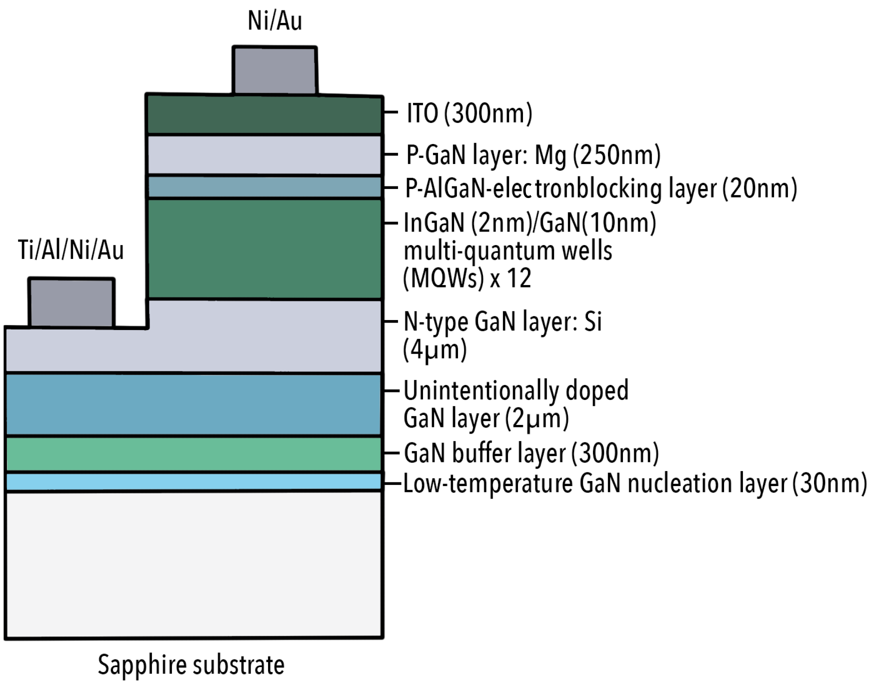


Fig: 10: Multiple quantum well (MQW) LED structure. (Khanna 2014)

Modern LEDs feature multiple quantum wells arranged in a periodic fashion. This way carrier confinement is granted by quantized electronic states and low tunneling probability. Also overflow related saturation issues are resolved by carrier distribution over numerous well structures. Corresponding to the nanoscale size of the active regions the concept of diffusion length becomes invalid to a certain extend what causes for current-voltage characteristics deviating from those of conventional p-n homojunctions (Khanna 2014, p. 129-137).

5.2 Semiconductor Materials for Solid-State Lighting

According to Khanna (2014) the materials, which are used to manufacture light emitting diodes have undergone significant developments since the first introduction of low brightness devices for indicator lamp applications (see chapter about the history of solid-state lighting for more information). For modern inorganic LEDs covering the visible spectrum aimed to facilitate efficient high brightness illumination, the family of III-V compound semiconductors proves to be suitable. Basically the compounds AlGaAs, AlGaInP and AlInGaN in their respective stoichiometric variations provide the material of choice for the current high brightness LEDs in production. They all meet the requirements that are essential for efficient light emission as well as feasibility of production. The following table shows the criteria materials have to fulfil to be adequate candidates for solid-state lighting (Khanna 2014).

Table 1: Quality criteria for materials in solid-state lighting. (Khanna 2014)

Qualities to look for while selecting materials for LED fabrication	
1.	Emission within visible spectrum range
2.	Direct energy band gap
3.	Robustness of lattice
4.	Ease of fabrication/availability of substrate for growth
5.	Ability to vary bandgap by alloying
6.	Reliability for high temperature/high power operation
7.	Desirable electrical and thermal properties like high electron mobility, wide band gap, and high thermal conductivity
8.	Benign nature

Most important is the capability to emit light in the near ultraviolet as well as the visible part of the electromagnetic spectrum. This involves an electronic structure that exhibits bandgap energies corresponding to the energies of the this range of radiation.

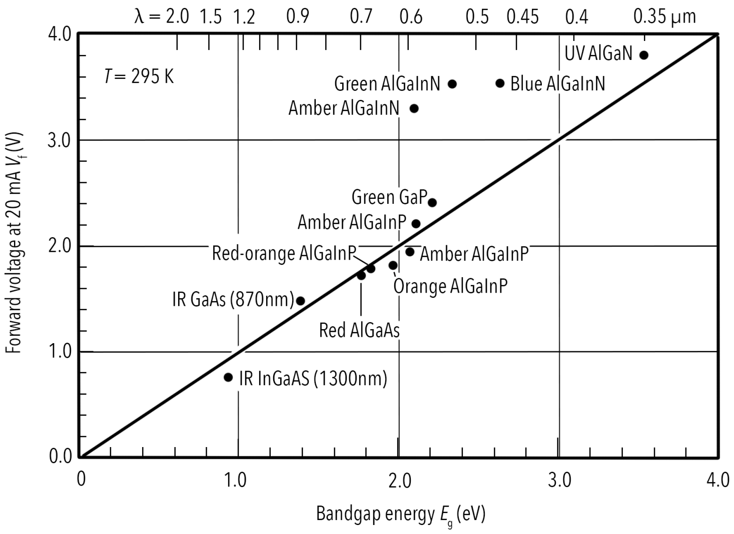


Fig. 11: Diagram of forward voltage across a light-emitting diode versus the band gap energy of different semiconductor materials. (Schubert 2006)

Next a direct bandgap transition is a fundamental prerequisite for a high rate of radiative recombination. This disqualifies the group IV elemental semiconductors and even some of the III-V compound semiconductors alike. Another criterion which should be matched is a low susceptibility to lattice defect formation and formation of centers for nonradiative combination. Moreover the lattice itself should be of physical and chemical robustness. An additional important aspect for the selection of appropriate materials is the ease of production and the availability of a fitting growth substrate. It is important in this respect that the choice of materials and the employed mode of fabrication are in good match. Furthermore the chosen materials have to have the ability to be tuned regarding their bandgaps in order to assemble structures of desirable properties. Compounds of group III and group IV elements can be mixed precisely by alloying in order to produce materials with favorable electronic properties. With LEDs heating up in a very punctual way, the used materials also need to feature corresponding coefficients of thermal expansion to prevent thermal disruption. In this context good thermal conductivity is also desirable to enable heat transport away from the active region. Also, electric resistivity of the incorporated materials should be low to reduce energy loss across the device. Finally it is preferable for the materials to be harmless to humans as well as the environment. (Khanna 2014, pp. 175-187)

One of the three most important material systems for modern LED fabrication is aluminum gallium arsenide (AlGaAs). Basically representing the fact that it is an arbitrary composition of gallium arsenide and aluminum arsenide the representation $Al_xGa_{1-x}As$ is often used. It has nearly the same lattice constant as GaAs which is therefore used as a growing substrate. By variation of the aluminum content bandgaps ranging from 1.42 eV for x=0 and 2.16 eV for x=1 can be achieved respectively. However only the portion for $0 < x < 0.45$ is of interest for LED production because of the switch to an indirect bandgap with larger aluminum contents. Because of the resulting direct to indirect transition at 1.985 eV corresponding to an emission wavelength of 624 nm AlGaAs LEDs are only suited for red to deep red applications. Maximum luminous efficiency is reached at λ = 640-650 nm at x = 0.35-0.4 with an internal quantum efficiency of 0.5. One considerable advantage of this material system arises from the possibility to grow different alloy compositions directly on top of each other due to the negligible lattice mismatch in comparison to the gallium arsenide substrate. This way the fabrication of heterostructures or even quantum well designs is easier to facilitate. However, AlGaAs alloys suffer from oxygen contaminations introduced during the fabrication process (liquid phase epitaxy) leading to an increased degradation of the material especially during operation under high-temperature and high-humidity conditions. (Khanna 2014, pp. 175-181)

In the range of shorter wavelengths than those emitted by aluminum gallium arsenide a composition of aluminum, gallium, indium and phosphorous is employed. AlGaInP is used to create heterostructures that emit red, orange, green and yellow light. Like AlGaAs this semiconducting alloy has a transition from direct bandgap to indirect bandgap at a certain amount of incorporated aluminum. In $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ the crossover to an indirect bandgap occurs for $x > 0.5$ at a bandgap energy of 2.33 eV which corresponds to a wavelength of 532 nm. However the exact position of the crossover point may be dependent on the degree of atomic ordering in individual materials.
Similar to the AlGaAs material system, $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is lattice matched to GaAs due to the high resemblance of atomic radii of aluminum and gallium. Therefore growth on GaAs substrates is rather unproblematic. (Schubert 2006, pp. 209ff.)
Moreover, the coefficients of thermal expansion of those materials are identical which avoids lattice strain and possible disruption during chip heating under operation. By growing transparent lattice matched GaP window layers on top of AlGaInP heterostructures the highest possible device efficiencies for this material system are reached. Most common crystal growth methods are vapor phase epitaxy (VPE) and LPE for deposition of GaP layers on the surface of AlGaInP double heterostructures. Though suited for the fabrication of LEDs emitting in the range of 652 nm (x=0) to about 580 nm (x=0.4) the radiative recombination rate declines for shorter wavelengths. This shortcoming can be attributed to the increasing convergence of direct- and indirect bandgaps in the electronic structure of the material. This diminishment is, to a certain extent, compensated by the increasing sensitivity of the human eye towards wavelengths approaching the green fraction of the visible spectrum. In terms of crystal growth, contamination with oxygen has to be thoroughly avoided in order to prevent deep level formation of compensating acceptors. The established technique to fabricate AlGaInP structures is metalorganic vapor phase deposition (MOCVD) allowing for good process control and high compositional flexibility while minimizing hydrogen or oxygen contamination. LEDs made from AlGaInP offer high luminous efficacies in the red spectral region and are well applicable for signal applications and illumination purposes due to their unproblematic operation in high power regimes (Khanna 2014, p. 182).

A breakthrough in solid-state lighting technology was achieved by the introduction of GaN based compound semiconductors. AlInGaN structures for the first time enabled the fabrication of high brightness LEDs in the green, blue and near ultraviolet color regime. (Schubert 2006, p. 211ff.) The bandgap of this material system can be tuned by the amount of indium introduced to the alloy. By variation of the indium to gallium ratio between values of 0.002/0.98 and 0.3/0.7 the according InN and GaN fractions determine emission colors of InGaN quantum well structures ranging from green to violet. Also, AlGaN of varied AlN proportions is used to fabricate cladding layers of quantum wells for ultraviolet LEDs. Despite the high density of crystal defects resulting from strong lattice mismatch with respect to substrate materials, high internal quantum efficiencies are realized with this material system. With their insensitivity to atomic dislocations and the lack of a direct to indirect bandgap transition in combination with high radiative efficiencies, LEDs based on gallium nitride surpass other systems like AlGaAs and AlGaInP. Furthermore low susceptibility to heat induced damage as well as high injection currents prove to be additional advantages. Paired with a suitable and efficient light converting phosphor blue III-V nitride LEDs are capable of producing white light for general illumination. Sustained development of those devices have led to a situation, where solid-state lighting poses serious competition to conventional light sources like halogen lamps or even fluorescent lamps. (Khanna 2014, pp. 184ff.)

5.3 Manufacturing of Inorganic LEDs

The fabrication of light emitting diodes requires diverse and sophisticated methods of production. Accordingly, the machinery in use has to be very precise and able to operate on a nanoscale level with consistent performance. Manufacturing of an LED starts with the substrate preparation followed by the deposition of the actual assembly of different semiconductor alloy layers constituting the actual die. After that, the individual chips have to be separated and passed on to packaging. With the packaging complete, the final LED lamp assembly is put together.

AlGaAs layers are produced using the low-priced LPE technique, while AlGaInP and AlInGaN structures utilize the more intricate MOCVD deposition method. Liquid phase epitaxy (LPE) commences with the blending of Al, GaAs and the necessary dopants in a purified gallium melt. To induce crystal growth a horizontal slider made of graphite located in a hydrogen filled quartz tube glides over a baseplate of the same material. The slider is equipped with cavities in which the molten semiconductor solutions including dopants reside. As the first cavity reaches the area with the seed crystal on the baseplate, the whole arrangement is cooled in order to create a supersaturated liquid. This allows AlGaAs to grow on the substrate. After the first layer has been grown in a well scrutinized temperature and time regime, the slider is moved on to bring the next solution into contact with the growth area. After a new heating cycle the furnace is cooled as before enabling the next crystal layer to grow on top of the previous one. This comparably simple method allows for speedy growth rates as well as the ability to grow pure and thick layers. For other material systems like AlGaInP and AlGaInN in particular some difficulties arise which necessitate the use of more refined techniques. As for AlGaInP the different thermodynamic stabilities of AlP and InP make it difficult to obtain homogeneous layer compositions. Furthermore aluminum segregation poses an additional problem. With regard to AlGaInN the high equilibrium pressure of nitrogen and high melting temperatures of nitrides cause problems. (Khanna 2014, pp. 191-219)

Metal organic chemical vapor deposition (MOCVD) features a non-equilibrium growth process that employs transport of source materials to the substrate by vapors. The evaporated precursors are conveyed to the target area by bubbling them into a carrier gas stream to form homogeneous crystal layers during deposition on a preheated target. In this process the precursors such as PH_3 for phosphorous and NH_3 for nitrogen deposition respectively (group V constituents) decompose on contact with the hot substrate. For group III elements to be incorporated into the epitaxial layers $Ga(CH_3)$ for gallium, $Al(CH_3)$ for aluminum, $In(CH_3)$ for indium SiH_4 for silicon, AsH_3 for arsenic and $Zn(C_2H_5)_2$ for zinc are used. The growth takes place in a reactor under a high pressure atmosphere of hydrogen. Utilizing this technique, typical growth rates of about 2µm/h can be achieved. MOCVD offers good performance in terms of reproducible crystal growth. Also the fabrication of abrupt thin layered heterostructures along with precise control of composition and doping are further advantages. Concerning drawbacks, the process cannot provide thick window layers necessary for high light extraction values in high power LEDs and some of the precursors are hazardous to health and environment. (Khanna 2014, p. 193-194)

The growth of epitaxial layers needs appropriate substrates. As point of origin of any LED structure a substrate or wafer has to exhibit some key features. Low electrical resistance, low absorption of light and minimal inclination to cause lattice defects are important requirements for the fabrication of efficient light emitting diodes. For the minimization of power loss high thermal and electrical conductivities are necessary. In order to reduce light loss, the substrate should be transparent to wavelengths emitted by the active region of the chip. Aside from offering a low defect density itself, the material of choice ought to match the epitaxial layers with respect to lattice spacing and thermal conductivity. GaAs proves to be a good substrate for the growth of AlGaAs and AlInGaP due to a small lattice mismatch. Usually the substrates are n-type doped with tellurium, sulfur, silicon or selenium and tin in rare cases. For some AlGaAs devices production starts with zinc doped p-type substrates. Doping has to be as heavy as possible to ensure good electrical conductivity. Reaching the limit of solubility has to be avoided to evade the formation of performance hindering precipitates and other structural defects. Phosphide materials can also be grown on GaP substrates although LED structures based on GaN are normally deposited on diverging materials like SiC, sapphire (Al_2O_3) or pure silicon on grounds of inadequate bulk growth methods at the time. Associated problems are the considerable lattice mismatch as well as large differences in thermal expansion. Moreover, high mobility of surface atoms at growth temperatures causes problems for a homogeneous layer deposition on the substrate. (Khanna 2014, pp. 194-219)

Table 2: Specifics of possible GaN substrates. (Khanna 2014)

Substrate	Lattice Parameter (nm)	TD Density (cm^{-2})	Available Wafer Size	Thermal Conductivity ($W\text{-}m^{-1}K^{-1}$)	Thermal Expansion Coefficient (K^{-1})	Cost
Sapphire	a=0.478 nm, c=1.2991	10^9	6"	20-40	$4\text{-}9 \times 10^{-6}$	Low
Silicon carbide (4H-SiC)	a=0.3073, c=1.0053	10^8	6"	490	2.77×10^{-6}	High
Silicon	a=0.543	$>10^9$	12"	150	2.6×10^{-6}	Lowest
Bulk gallium nitride	a=0.319, c=0.518	10^6	2"	250	$3\text{-}5 \times 10^{-6}$	Highest

To cope with this difficulties buffer layers made of AlN or GaN have to be laid out on the substrate at lower temperatures before the actual main layer can be deposited. Consequently the quality of the deposited layer is strongly determined by the quality of the buffer layer. Despite that, dislocation density in GaN materials stays very high and it is only due to not yet fully understood internal compensation mechanisms that production of efficient structures is feasible (Schubert 2006, pp. 226-231). Bending of grown layers because of different thermal expansion coefficients is also a problem. Regarding the growth of GaN on silicon substrates the presence of cracks between atomic layers and the emerging scattering centers cause for lower quality layers compared to those grown on sapphire. In addition to the crystal growth itself complemental fabrication steps need to be considered as well. Doping is decisive for the functional quality of the LED structures and is also carried out in the MOCVD reactor. Here gas flow and temperature have to be fastidiously controlled to reach a well distributed and appropriate carrier concentration. Moreover contacting of the finished and doped semiconductor structures is crucial. The contact areas should provide linear, symmetric and temperature independent current-voltage characteristics. N-type GaN chips are commonly contacted by pads consisting of a Ti/Al/Ni/Au (thicknesses: 100/200/40/50 nm) metal layered structure to facilitate a stable oxidation- and diffusion proof electrical connection. Contacting of p-type layers proves to be more difficult. Low carrier concentrations of the magnesium doping based on small activation energy require metal contacts with high work functions. Usually Ni/Au schemes with layer thicknesses of 20/100 nm are applied. (Khanna 2014, p. 194)

The metal contact layers are usually deposited by various techniques of metal evaporation. After either resistive, inductive (radio frequency), electron bombardment or laser heating, the vaporized metal condenses on the desired spots predetermined by lithography. Sputtering is a process that surpasses evaporation techniques in terms of process control. To bring LED dies into the appropriate shape for further production steps, unneeded material has to be removed. Lift off of dispensable layer parts or the substrate is carried out by etching. Due to the high chemical stability of GaN only chemically aggressive techniques can be applied. Boiling acids such as H_3PO_4 or H_2SO_4 or strong alkaline solutions like NaOH and KOH are used to etch the material with the drawback of producing jagged surfaces. This outcome can be attributed to their proneness to corrode crystal defects. To cope with that, anisotropic etching using halogen-based compounds under inert gas atmospheres as well as ion bombardment are employed. Inductively coupled plasmas (ICPs) with high plasma densities are also used to etch active structures made from nitrides. With regard to the removal of high-hardness sapphire substrates, excimer laser irradiation is preferred over polishing procedures. By forming a split zone induced by strong local heating resulting in the generation of gallium droplets and gaseous nitrogen, the active region can be lifted off the substrate after some thermal annealing. The surface of the removed dies is then roughened by etching to increase the ability to couple out light.

In summary, the fabrication of LED dies requires versatile methods of microstructure production. Most important are: LPE, MOCVD, photolithography, mesa etching, metal deposition, lift off and annealing. (Khanna 2014, pp. 198-205)

5.4 High Efficiency LED-Packages

Design of current flow plays an important role in the fabrication of efficient light emitting diodes. Metallic contacts are opaque to visible light emitted by the diode, whereas the pattern of current spreading across the structure has to be extensive in order to achieve high extraction efficiencies. One strategy to avoid light loss due to useless emission under the contact pads is the incorporation of a current spreading layer (synonymous with window layer). It helps to spread out light emission from the small perimeter of the contact to a larger light emitting area.

Desirable properties of a current spreading layer are transparency to the emission wavelength of the chip, a high thickness to facilitate current spreading and low electrical resistivity. AlGaInP structures can be equipped with GaP window layers. It has an indirect bandgap of higher energy (2.26 eV) than AlGaInP and therefore offers good transparencies for the emitted wavelengths. Nonetheless a possible problem can emerge due to the fact that GaP is lattice mismatched to the underlying epitaxial layers. If the resulting dislocations should propagate towards the active region during operation, they might act as centers of non-radiative recombination thus diminishing the extraction efficiency. AlGaAs window layers avoid these issues by better lattice matching with respect to the cladding layers but struggle with local variation of bandgap energies caused by fluctuations in compositional cation concentrations. Also compounds containing aluminum need very high process qualities in order to avoid unwanted degradation by oxygen during fabrication or operation. Under optimal conditions regarding layer thickness, absorption properties and electrical resistance of the used material, efficiency increases by a factor of 30 can be achieved. For GaN the application of window layers is confronted with poor conductivity of p-type layers. This problem can be solved by the introduction of a tunnel junction contacting the positively doped confinement region adjacent to the active region. Consequently the LED structure features two n-type contacts in contrary to a normal design with one p-type and one n-type contact each. (Schubert 2006, pp. 127-133)

Another effect affecting the current spreading underneath metal contacts appears in mesa structure LEDs utilizing the GaInN/GaN material system. Those structures are grown on isolating sapphire as a substrate. Due to the geometry of the structure, the current tends to crowd beneath the edge of the n-type contact facing towards the mesa.

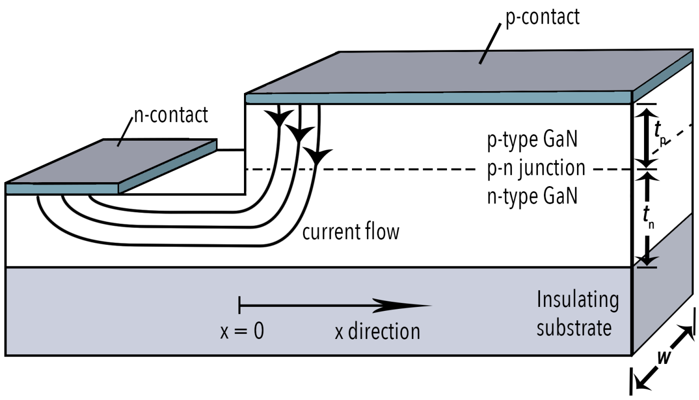


Fig. 12: Schematic image of current crowding in an LED. The depicted mesa-structure is based on GaN and was grown on an insulating substrate. (Schubert 2006)

To address this problem, which is especially severe for high power LEDs since punctual heating is involved, new contact geometries have to be implemented. Interdigitated stripe contact structures help to cope with those difficulties by evenly distributing the current across the whole chip. This is accomplished by designing the p-type contact width smaller than the current spreading length. Additionally the n-type contact has to be identical to the contact transfer length at least to provide acceptably low contact resistance. (Schubert 2006, pp. 136-140)

Another scheme of injection is lateral injection. It offers the advantage of unobstructed light emission since the contact areas are not in the escape path of the emitted light. Current transport takes place laterally in both the n-type and p-type cladding layers.

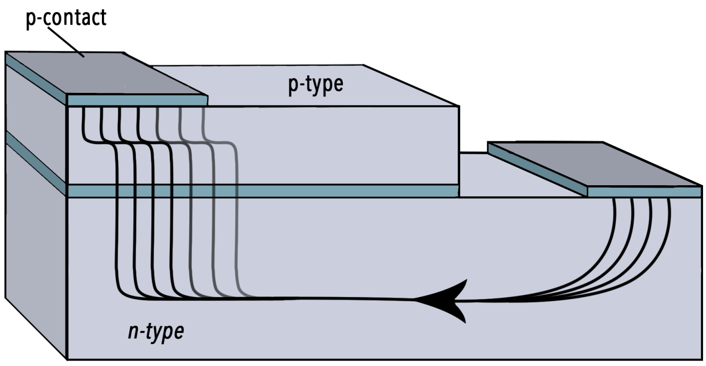


Fig. 13: Lateral injection geometry based mesa-structure. (Schubert 2006)

For large discrepancies of the n- and p-type materials in terms of resistivity, current crowding around the p-contact can also become a problem. By increasing the thickness of the confinement layers in order to enhance current transport or, in most cases more practical, the downscaling of device size along with incorporation in multi structure arrays this problem can be alleviated. For structures on conducting substrates featuring large backside contacts in comparison with small top contacts, current blocking layers help to maintain a uniform distribution of injection current. Those layers prevent currents from entering the active region directly below the contact area. No or very little light emission takes place under the opaque metal contact thus increasing the extraction efficiency of the device.

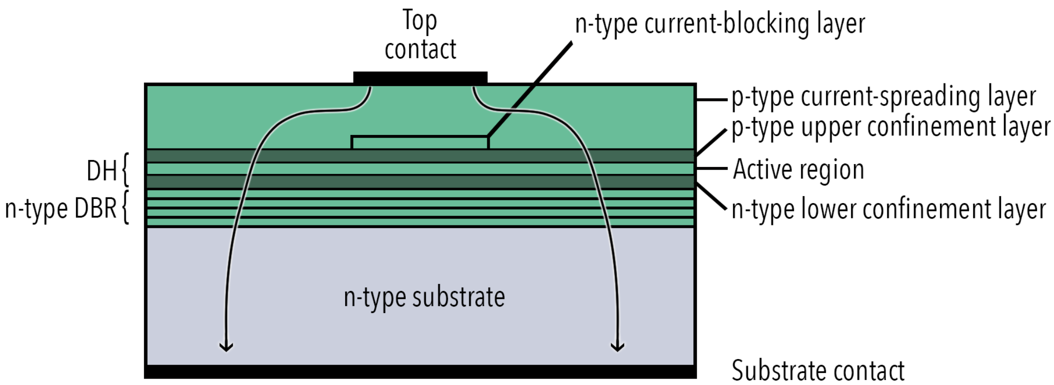


Fig. 14: Double heterostructure LED featuring an n-type current blocking-layer situated above the upper confinement layer. Emission takes place in the regions, which are not obstructed by the opaque top ohmic contact. In using the technique of epitaxial regrowth, the wafer is removed from the crystal-growth system for etching after the growth of the current blocking layer. Subsequently the wafer is once again introduced to the epitaxial growth system for deposition of a current spreading layer. (Schubert 2006)

The insertion of a blocking layer is mostly performed by epitaxial regrowth making it a time consuming and expensive procedure. Therefore, it is limited to high performance devices. This is a result of the fact that epitaxial layer growth has to be interrupted to allow for an etching step in which the parts of the most recent grown blocking layer that will not be located beneath the contact are removed. Etching involves increased discard, requires advanced cleaning and has to be carried out very carefully to avoid the formation of defects in underlying material. The structures are subsequently reintroduced to the growing process.

Top contacts can be optimized by refining their shape. To provide better current distribution across the active region of the chip, simple circular bond pads are replaced by cross or ring shaped geometries. Nonetheless, minimization of the contact area to promote light escape remains a desirable objective. (Schubert 2006, pp. 140-143)

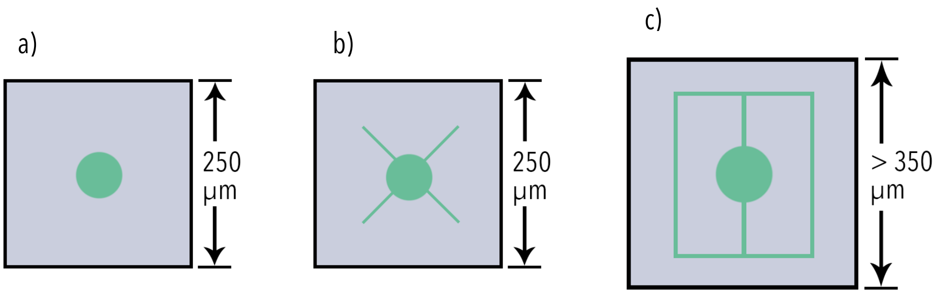


Fig. 15: LED topside contacts.

a) A circular contact also used as bond pad, b) a cross-shaped contact with a circular bond pad and c) a common contact shape used for larger chip structures. (Schubert 2006)

For the enhancement of light extraction efficiency, transparent substrates are sometimes used to substitute for the absorbing growth substrates. Especially AlGaInP LEDs emitting wavelengths between 560-660 nm suffer from absorption of GaAs substrates due to its 1.424 eV bandgap corresponding to radiation of 870 nm. The significant absorption of the substrate can be eliminated by removal of the GaAs layer and its consecutive replacement by a new substrate layer of GaP. This material exhibits a large enough indirect bandgap (2.24 eV corresponding to λ=553 nm) and thus does not absorb emitted light. (Schubert 2006, p. 156)

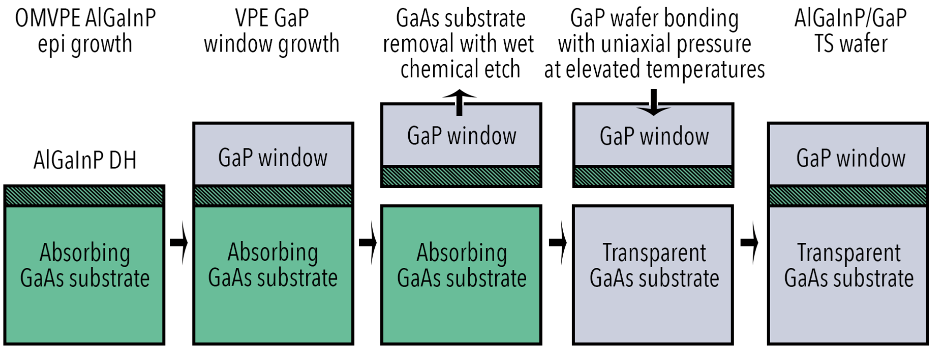


Fig. 16: Simplified manufacturing process for wafer-bonded transparent substrate AlGaInP/GaP structures. Subsequent to the removal of the original GaAs substrate the formation of a single transparent substrate structure is achieved by the application of elevated temperature and uniaxial pressure. (Schubert 2006)

The process of substrate substitution is complex. Etching processes and substrate bonding require the exclusion of any surface contaminants. Also, correct lattice alignment plays an important role in reaching high efficiencies.

Another loss mechanism diminishing light extraction is light reflection at the semiconductor-air interface. Anti-reflection coatings are used to cope with this issue. By deposition of dielectric materials like silica, alumina or silicon nitride with adequate refractive indices, reflective losses can be substantially reduced (Schubert 2006, pp. 156-160).

On the other hand, highly reflective materials can be used to increase chip performance. Different kinds of more or less sophisticated reflectors are nowadays incorporated into LED devices reaching from simple metallic reflectors and total internal reflectors to distributed Bragg reflectors and their respective hybrids as well as omnidirectional reflectors. In terms of reflectivity, due to the smaller difference of their respective refractive indices, metal-semiconductor reflectors do not supply results as satisfying as those of metal-air reflectors. Reflective layers can be included into LED structures by deposition of pure metals or alloys. By conducting a subsequent annealing step alloyed contacts with lower contact resistances are obtained. Simple metallic reflectors hold the disadvantage of considerable losses in the event of multiple reflection events. However, in order to increase light extraction in LED dies grown on transparent substrates, a silver saturated die-attach epoxy can be used. Forming a high reflectivity material which covers the areas not obstructed by the ohmic backside contacts of the die it also provides a good mechanical connection to the packaging at the same time. For dies grown on light absorbing substrates, very effective reflectors are needed to avoid significant losses in light extraction.

One method to do so features the placement of distributed Bragg reflectors (DBR) between the active region and the substrate. Light emitted by the active region is therefore always directed to the top side of the chip where it is able to escape from the assembly. (Schubert 2006, pp. 163-180)

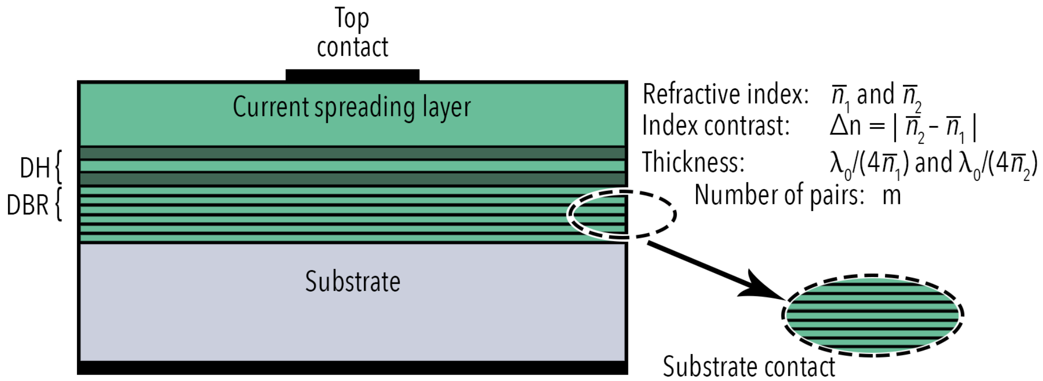


Fig. 17: Double heterostructure LED with a distributed Bragg reflector (DBR) situated between the substrate and the lower confinement layer. (Schubert 2006)

A distributed Bragg reflector consists of a stack of multiple layer reflectors usually comprising 5-50 pairs of two materials of differing refractive indices. High index contrasts yield better results. Fresnel reflection occurs at every single interface. In order to maximize this type of cumulative reflection, thicknesses of the layers are arranged in a fashion, which promotes constructive interference between the reflected waves. Both transparency for the wavelength of operation and lattice match to the used double heterostructure are also important criteria for an effective DBR. If the device current passes through the reflector during operation, good electrical conductivity is crucial as well. Due to the fact that layer thicknesses of DBRs are preferably adjusted to match one quarter of the incident light wave, the reflectivity becomes angle dependent. If the angle of incidence exceeds a critical angle the reflectivity drops rapidly. Therefore, most DBRs are not suitable for omnidirectional reflectors. Those disadvantages can be attenuated by careful selection of refractive indices and absorption spectra of the used materials. (Schubert 2006, pp. 163-180; Liu and Luo 2011, pp. 43ff.)

Omnidirectional reflectors (ODRs) featuring high electrical conductivities are most desirable in order to gain high extraction efficiencies in LED lighting. One promising approach is to utilize three layered hybrid reflectors. They consist of a semiconductor layer adjacent to a dielectric layer perforated by an array of micro contacts followed by a metal layer. This grants for a broad spectrum of reflectivity as well as omnidirectional characteristics. Additionally roughening of the reflective surfaces to achieve a Lambertian pattern of reflection also enhances the extraction of light by the reduction of total internal reflection incidents. (Schubert 2006, p. 181)

6 Wavelength Converters in Solid-State Lighting

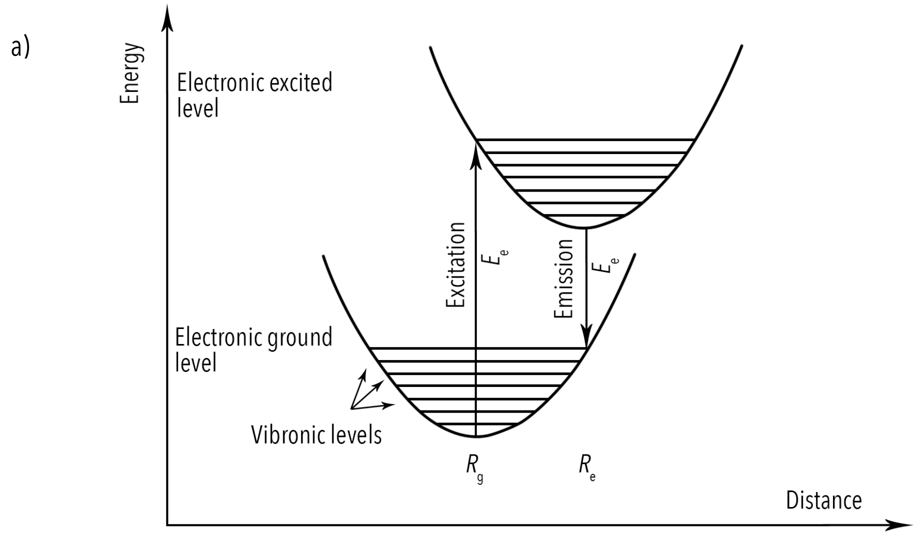
The details on composition and working principles of phosphors were taken from technical literature published by Khanh et al. (2015), Khanna (2014), Liu and Luo (2011) and Schubert (2006).

One fundamental part of current high efficiency solid-state lighting is wavelength conversion. Due to the fact that multi-color LED arrays featuring the fundamental colors red, green and blue show reduced efficiencies while exhibiting increased degrees of device complexity, the conversion of short wavelength radiation in the UV- or blue portion of the spectrum combined with a down converting phosphor is the predominant technical solution. The physical working principles of phosphors as well as their basic chemical structure and most important material compositions are treated in the following chapter. (Khanh et al. 2015, pp. 72-82)

6.1 Physical Principles of Phosphors

Phosphors are artificially produced crystalline substances, which feature the physical phenomenon of light-induced (photo-) luminescence. Under irradiation by electromagnetic waves the phosphor gets energized and then reemits the absorbed light after a certain loss in energy as radiation of longer wavelengths. Dependent upon the timespan in which the reemission takes place, one discerns between fluorescence and phosphorescence. In fluorescence the time between absorption and emission occurs within tens of nanoseconds while phosphorescence shows an afterglow of more than one millisecond up to several hours. The mechanism determining the type of energy transformation and its duration depends on the nature of the excited state. However the emission following the initiation of an excited state is always accompanied by a loss in energy called the Stokes shift. This difference in energy is transformed to lattice vibrations of the crystal and results in heating of the substance. (Khanna 2014, pp. 277-290; Yen et al. 2006, pp. 72-82)

Phosphors are inorganic polycrystalline materials, which are commonly activated by the introduction of small concentrations of dopant ions also called emission centers or activators. Phosphors used in white LEDs usually harness the optical transitions of the luminescent centers leading to broad emission spectra with bandwidths of more than 50 nm for the most commonly used activator ions Ce^{3+} and Eu^{2+}. Those emission characteristics are a result of differing bond lengths for the excited and ground states in the chemical compound. In the event of luminescence the equilibrium distance between the emission center and the adjacent lattice atoms (ligands) can be described by the configuration coordinate diagram. This model characterizes the potential energy of an activator ion and its nearest neighbor ion in the crystal lattice as a function of the gap between them. In this way the bond length between activator and ligands can be plotted for the ground state as well as the excited state. (Khanh et al. 2015, pp. 72-82)



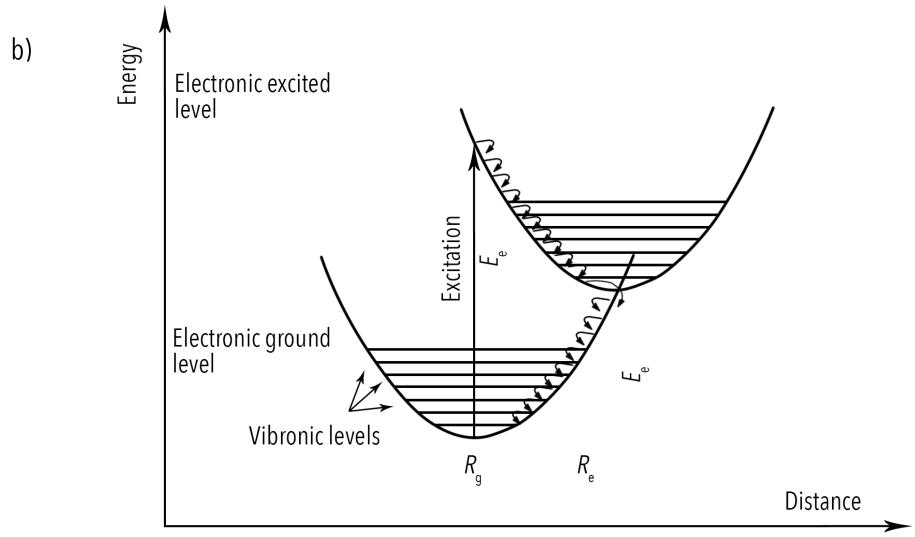


Fig. 18: Configurational coordinate diagram.

a) Emission of light is enabled due to lack of parabolic crossing.

b) Emission is suppressed by parabolic crossing. Relaxation happens via non-emissive paths. (Khanh et al. 2015)

In the figure above two cases are shown. The first part illustrates the situation, when emission involving a change in bond length is able to happen. The second part shows the case in which a sufficient change of bond length for a specific energy of the excited state alters enough to prevent emission from happening. The same change of bond distance between the ground and the excited state can lead to this effect for different energies of excited states. In this case the electrons can relax from the excited state to the ground state via a non-emissive path. Additionally, relaxation without the emission of light can occur for constant energies of the excited state but more intense changes of bond length. Therefore, the diagram can be used to visualize the connection between the process of relaxation and the Stokes shift, which stands in close relation to the observed thermal behavior or the lack of luminescence in certain phosphor materials. Thus the model is also often used to describe thermally induced luminescence quenching (so-called effect of temperature quenching). Even though no parabola crossing might occur at lower vibronic levels, an electron might be excited to higher levels by thermal energy where crossing is possible. Nonetheless the configurational coordinate diagram, as opposed to the model of energy-bands, cannot explain the process of photoionization. By using the band model this quenching mechanism can be explained by the proximity of the excitation level to the bottom of the conduction band. Being initially located on the activator ion excited electrons can nevertheless escape into the conduction band of the surrounding crystal lattice. The probability for such an event to happen increases with raised temperatures since thermally provided activation energy becomes available for the promotion of electrons into the conduction band. (Khanh et al. 2015, pp. 72-82)

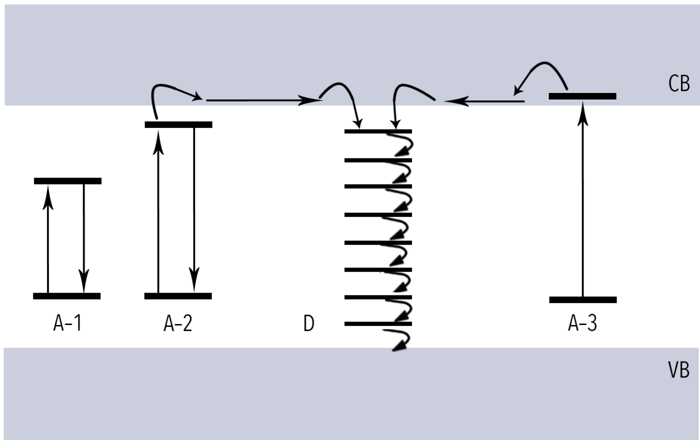


Fig. 19: Simplified illustration of the photoionization process. A1, A2 and A3 represent activator ions with different excitation energies. For this depiction it is assumed that their ground states are equal with respect to the valence band. D represents a defect site. (Khanh et al. 2015)

The figure above shows, among other examples, a case when the emission level of the activator is situated well below the conduction band. Thermally induced photoionization does not impede the emission of light. For smaller differences in energy between the emitting state and the bottom of the conduction band the emission can be inhibited by elevated temperatures due to increased number of photoionization processes. This mechanism is dominant for activators, which hold emission states located within the conduction band of their host lattice. In this case, no emission can be observed. Another important quenching mechanism is the phenomenon of electron or charge carrier hopping. Electron hopping can be the result of two different processes. First concentration quenching can be observed when the concentration of dopant ions exceeds a certain value. Too high concentrations facilitate the interaction between excited activator ions as they become able to exchange excited electrons due to their close vicinity. If those hopping electrons reach the site of a lattice defect luminescence will be quenched. Second thermally induced electron hopping occurs when electrons on excited dopant levels experience increased mobility as a result of available thermal energy causing them to finally transfer to a defect site where they are lost due to non-radiative recombination. A setting in which those two possibilities for charge carrier hopping appear together to cause thermally induced luminescence quenching is highly probable. (Khanh et al. 2015, pp. 72-82)

Essential for the use of phosphors in solid-state lighting is their capability to efficiently absorb photons emitted by LED dies and transform them into suitably colored light of the visible spectrum. Since this transformation always is connected to Stokes shift the emission spectrum of the LED chip has to be in the regime of shorter wavelengths than the desired light output of the phosphor. Normally those spectra lie within the range of near ultraviolet (350-410 nm) to blue light (440-470 nm) (Khanna 2014, p. 278). The dopant ions, also denoted as activators or luminescent centers, are represented by metal ions, which replace a small portion of cations in the host lattice. Those ions facilitate the process of emission by electronic transitions between discrete levels of energy. Energetically located in the bandgap of the host lattice the gaps between those quantized states strongly depend on the chosen activator ions. Also, the type of dopant used decisively influences the quality of emission spectra. Broad or sharp peaks or a combination of both respectively can be observed with different combinations of host lattices and activators. Despite the fact that a large number of various ions are able to show photoluminescence once introduced to a suitable host lattice, rare-earth (RE) ions are considered to be the most eligible. Their singular electronic structure allows for rather narrow atomic-like emission lines (f-f transitions) only a few nanometers wide or very broad emission bands (d-f or charge transfer emissions) spanning about 200 nm. The unique narrowness f-f transition emission peaks is caused by the shielding of 4f orbitals by the outer 5s and 5p orbitals. Therefore 4f orbitals do not participate in chemical bonding leaving them rather unaffected by their chemical surroundings. As a result the emission lines show only small variations between differing host lattices, however their relative intensities can be modeled by adapted quantum theory (e.g. Judd-Ofelt theory). Opposed to that, the emission lines of transitions entailing 5d orbitals are strongly influenced by the chemical environment because of their participation in chemical bonding. Therefore as fundamental parts of the host lattice, the ligands bound to the dopants execute strong effects on the energy levels related to the 5d orbitals. Hence the dedicated selection of host materials permits the fabrication of tailored absorption and emission spectra for the same dopant ion. Also for the case of 5d states some theoretical models exist to predict the properties of the desired phosphor material. In order to tune the properties of phosphors to fit the meant application a suitable rare-earth cation must be chosen. Different rare earth cations feature respective luminescence characteristics on the basis of differing electronic transitions. Those can be quantum mechanically allowed, partially allowed or forbidden. Qualities like luminescence intensity, temperature quenching of luminescence or emission lifetime are influenced by the choice of activators and their ligands. For some combinations the incorporation of sensitizer ions becomes necessary to increase the efficiency of luminescence of an activator ion. By doing so, poor absorption abilities in the range of excitation energies can be resolved due to increased energy transfer to luminescence centers. (Khanh 2015, pp. 73-82.; Yen et al. 2006)

One of the most important parameters for the characterization of phosphors is the quantum efficiency (QE). It denotes the capability of a phosphor to reemit photons that have been absorbed in the first place. Here it is relevant to note that there are two types of quantum efficiencies: Internal QE and external QE. The internal quantum efficiency QE_{int} is described by the ratio between the quantity of photons emitted by the phosphor material and the number of photons absorbed. The external quantum efficiency QE_{ext} on the other hand describes the ratio between the quantity of emitted photons and the quantity of pump photons.

$$QE_{int} = \frac{\# \quad photons \quad emitted}{\# \quad photons \quad absorbed} \tag{6.1}$$

$$QE_{ext} = \frac{\# \quad photons \quad emitted}{\# \quad pump \quad photons} \tag{6.2}$$

Due to the fact that the number of pump photons will always be higher than the number of absorbed photons the magnitude of QE_{int} is always larger than the value for QE_{ext}. Only for an ideal case, when the number of pumped photons conforms to the number of absorbed photons, those two values will be identical. All in all the determination of quantum efficiencies for phosphors is a non-trivial matter and requires intricate methods of measurement. Some of those include single photon counting techniques and the measurement of emission lifetimes under special conditions such as low temperatures and excitation of lowest possible states in an effort to exclude the possibilities for non-radiative relaxations. Moreover the emission lifetime is another important parameter when it comes to determining the applicability of certain phosphor materials for the use in solid-state lighting devices. This value gives information about the tendency for saturation under the excitation by high light fluxes common for high performance LED dies. It is specified by the time it takes for the intensity of emission to drop to a value of 1/e of the initial intensity. The decay time or emission lifetime needs to be short enough to prevent saturation of luminescence in the activator ions. Saturation occurs when the exciting light flux is high enough to excite all available activators causing a depletion of ground states. In this case the emission lifetime is too long, leaving excited electrons with insufficient time to recombine radiatively. This highly undesirable effect can be mitigated by detaching the phosphor from direct contact to the LED chip and therefore reducing the flux of excitation light impinging on phosphor particles (concept of remote phosphor). Another way is the choice of activator ions that exhibit short enough emission lifetimes in the range of tens of nanoseconds to a few microseconds. Mostly activators that feature fully allowed electronic transitions show decay times in this range. Emission lifetimes in the millisecond range are mostly unsuitable and advise a use in remote configurations. (Khanh et al. 2015, pp. 72-82.; Yen et al. 2006, pp. 533-540)

6.2 Materials for LED Light Converters

6.2.1 Aluminum Garnets

$Y_3Al_5O_{12}:Ce^{3+}$ (YAG:Ce) and $Lu_3Al_5O_{12}:Ce^{3+}$ (LuAg:Ce) have become very popular representatives of the aluminum garnet family not only for the use in solid-state lighting but also for scintillator materials. Due to its highly organized garnet structure this material proves to feature very stable luminescence at elevated temperatures when doped with suitable activator ions. Synthesis of this phosphor can be conducted in a wide range of temperatures from 800 to 1800 °C, whereas higher temperatures result in increased crystal quality. In terms of use and adaption YAG:Ce^{3+} has been the most utilized phosphor in solid-state lighting. Its emission spectrum lies in the yellow region of the visible spectrum at about 550 nm induced by the transition of the lowest f-d state of cerium to its ground state. The Stokes shift between the maximum of the lowest excitation band and the maximum of the emission band is approximately 2800 cm^{-1}. The value of full width at half maximum (FWHM) is represented by a rather broad emission band of about 2400 cm^{-1}. Those values can be manipulated by the dopant content of cerium ions. Increased amounts of cerium for instance lead to a redshift as well as broadening of the emission spectrum. YAG:Ce^{3+} phosphors show very high quantum efficiencies reaching from 95 to 100%. As a consequence of the relatively low Stokes shift and comparably large optical bandgap (E_g = 6.9 eV) the onset of temperature quenching is situated at about 600 K. Usually the yellow phosphor is combined with a (In,Ga)N LED emitting in the blue range at about 450-480 nm resulting in a cold white color impression. Due to poor color rendering this combination is mostly restricted to the use in flashlights or non-domestic illumination.

LuAg:Ce^{3+} exhibits a blueshifted emission spectrum in comparison to YAG:Ce^{3+} which is located at about 500 nm. Like in YAG:Ce^{3+} the emission is a result of the transition from the excited fd state of trivalent cerium to the ground state. However with 2300 cm^{-1} and 1900 cm^{-1} respectively the Stokes shift and the FWHM are significantly smaller than the values observed with YAG:Ce^{3+}. Quantum efficiencies are in a comparable range of 90-100%. Because of its large optical bandgap (E_g = 7.5 eV) and the minor Stokes shift in comparison to YAG the onset temperature for thermal quenching lies even higher at about 700 K.

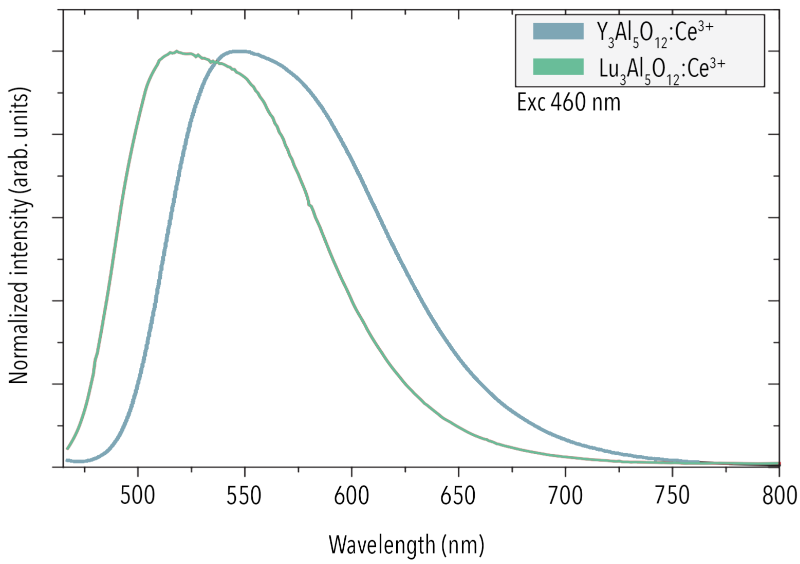


Fig. 20: Emission spectra of LuAg:Ce^{3+} and YAG:Ce^{3+}. (Khanh et al. 2015)

Even though the emission spectra of those materials lack a red component what proves to be problematic in producing devices with high color rendering indices their high chemical stability and inexpensive synthesis in combination with their superior temperature properties often lead to the use as standard for other phosphor materials. Novel phosphors emitting in the yellow to green range should perform at least closely to yttrium and lutetium garnets activated with trivalent cerium ions. Nonetheless the so-called cyan gap, which describes weak emission in the spectral region between the blue LED die and the yellow/green phosphor as well as the lack of red spectral portions necessitate the addition of additional phosphor materials in order to substantially improve color rendering and color related temperature of LED devices using aluminum garnets. By putting secondary phosphors into those devices new problems like raised energy loss caused by additional Stokes shift and difficulties in mixing and incorporation into carrier materials arise. Regardless, those issues are condoned by the lighting industry since light quality is an important factor in customer acceptance. Finally there are also other aluminum garnet compositions that can be used to fabricate phosphors. Possible materials are $(Y,Gd)_3Al_5O_{12}:Ce^{3+}$, $Y_3(Al,Ga)_5O_{12}:Ce^{3+}$ or $Tb_3Al_5O_{12}:Ce^{3+}$ (TAG:Ce^{3+}). Those materials show altered crystal structures leading to different crystal fields affecting the dopant ions. As a consequence the emission spectra experience a blueshift for $Y_3(Al,Ga)_5O_{12}:Ce^{3+}$ and a redshift for $(Y,Gd)_3Al_5O_{12}:Ce^{3+}$ respectively. As far as TAG is concerned, the large Terbium content allows for a slightly improved emission pattern with added portions of red light. However the mentioned materials show seriously deteriorated thermal stability of luminescence in comparison with YAG:Ce^{3+}. Moreover Terbium has a considerable price disadvantage that cannot be justified by the marginally improved emission characteristics it generates. (Khanh et al. 2015, pp. 82-86.; Yen et al. 2006, pp. 534-540)

6.2.2 Alkaline Earth Sulfides

Generally alkaline earth sulfide materials ($MS:Eu^{2+}$, M = Mg, Ca, Sr, Ba) using divalent europium ions as activators exhibit emission in the spectral region ranging from orange to red. They have been investigated for their luminescent properties with different activator ions like trivalent cerium, divalent europium, transition metal ions (Cu^{+}, Ag^{+}, Au^{+}, Mn^{2+}, Cd^{2+}) or s^2 ions (Bi^{3+}, Pb^{2+}, Sb^{3+}, Sn^{2+}). Until the introduction of red-emitting nitride-based phosphors alkaline earth sulfide phosphors were intended to be used in white LED devices in combination with $YAG:Ce^{3+}$ in order to complement the otherwise bluish-white emission spectrum. But deficiencies like low quantum efficiencies and poor thermal stability of luminescence hindered those materials from becoming widely adopted. Calcium based phosphors only show quantum efficiencies of 53% while $SrS:Eu^{2+}$ materials only yield 31%. Though the performance of alkaline earth sulfide phosphors strongly depends on quality of fabrication and it is important to note that those materials generally struggle with problems regarding their chemical composition. The incorporation of sulfide ions into the host lattice proves to be rather unstable under suboptimal circumstances of production. Resulting lattice defects and unwanted oxygen absorption heavily diminish performance. Furthermore the synthesis of the sulfides itself causes problems. The need for the highly toxic precursor H_2S necessitates thorough precautions to avoid health dangers and environmental hazards. Moreover the low optical bandgaps of sulfides promote thermally induced photoionization leading to strong thermal quenching of luminescence. Since modern high power LEDs operate at temperatures of about 150 °C intense losses in conversion efficiencies are to be expected. In the end sulfide materials are highly sensitive to the influences of moisture and air. The resultant accelerated degradation under ambient conditions greatly reduces their capability to be employed in durable luminaires. (Khanh et al. 2015, pp. 86-88)

6.2.3 Alkaline Earth Ortho-Silicates

The use of alkaline earth ortho-silicates $M_2SiO_4:Eu^{2+}$ (M = Ca, Sr, Ba) proves to be suitable in general lighting applications because of their emission in the yellow to orange-reddish portion of the visible range. Those compounds can be used to substitute $YAG:Ce^{3+}$ when tuned to emit yellow light or incorporated into a phosphor mixture. By utilizing phosphor blends with $YAG:Ce^{3+}$ a substantial improvement in color correlated temperature towards a warm white impression and an elevated color rendering capacity can be achieved. Preparing compositions only containing Sr^{2+} yields orange emission (about 570 nm) whereas pure Ca^{2+} compounds yield deep-orange emission (about 600 nm). Additionally the range of possible chromaticities is extended by the use of solely barium, yielding light emission in the blueish-green spectral region (about 500 nm). The specific concentration of divalent europium ions in the compounds is another parameter, which influences the emission color. Higher concentrations cause a redshift in general. In alkaline earth ortho-silicates the luminescence stems from a transition of the lowest excited fd state to the ground state of Eu^{2+} and shows as a single emission band. Due to small FWHM values ortho-silicates feature emission of high color purity making them suitable for applications requiring high color rendering indices (e.g. $Ba_2SiO_4:Eu^{2+}$: FWHM = 2360 cm^{-1}; $Sr_2SiO_4:Eu^{2+}$: FWHM = 3200 cm^{-1}; Ca_2SiO_4: Eu^{2+} FWHM = 3160 cm^{-1}). On the basis of the similarity of their physical properties ortho-silicates can be mixed in order to reach broadened emission spectra yielded by chemically stable phosphor blends. Caused by the great variety of possible silicate compounds the fabrication of specific materials proves to be complex and necessitates tailored synthesis methods. Alkaline earth ortho-silicates feature very high quantum efficiencies of 90-100%. (Khanh et al. 2015, pp. 89-92)

6.2.4 Alkaline Earth Oxy-Ortho-Silicates

Alkaline Earth Oxy-Ortho-Silicates $M_3SiO_5:Eu^{2+}$ (M = Ca, Sr, Ba) represent another modification of the very diverse set of silicate materials. Emission-wise one can observe a slight redshift in comparison to the analogous ortho-silicates. Depending on the composition of the lattice the emission spectrum ranges from 570 nm for pure Ba^{2+} to 600 nm for pure Ca^{2+} content respectively. One big advantage of those compounds is the very high quantum efficiency of up to 100%. Exemplary FHWM values for some compounds are 2790 cm^{-1} for $Ba_3SiO_5:Eu^{2+}$, 3850 cm^{-1} for $Sr_3SiO_5:Eu^{2+}$ and 3370 cm^{-1} for $Ca_3SiO_5:Eu^{2+}$ respectively. Precise values regarding emission wavelength and spectral distribution depend on the respective dopant concentrations and specific chemical compositions. Consequently the possibility for tailoring emission colors and spectral broadness proves to be beneficial for the fabrication of alkaline earth oxy-ortho-silicate phosphors for general lighting applications. In this scope of application creating light resembling the spectral distribution of daylight with the aid of broadband orange/red phosphors is most desirable. (Khanh et al. 2015, pp. 92-93)

6.2.5 Nitride Phosphors

Ongoing from their introduction the class of nitride-based phosphors has reached a high degree of relevance. Facilitating the combination of red and green emitting nitride phosphors with a yellow phosphor (e.g. $YAG:Ce^{3+}$) remarkably higher color rendering capabilities can be achieved compared to single phosphor approaches. Also the correlated color temperature can be shifted towards a warm white impression.

One member of the nitride family is the phosphor $CaAlSiN_3$ ($CASN:Eu^{2+}$). It has a wurtzite-type structure and features a broad excitation band ranging from around 250 nm to 600 nm with a maximum at 450 nm. Because of that the compound is well suited to be operated with a blue LED chip for excitation. Also $CASn:Eu^{2+}$ can be operated with near UV LEDs showing only small penalties in excitation sensitivity compared to excitation by a blue chip. Concerning the emission spectrum of $CASN:Eu^{2+}$ a broad range spans from 550 nm up to slightly above 800 nm. The FWHM is rather narrow (95 nm) and the emission peak is located at 650 nm. When combined with a blue LED die and an additional green phosphor, those properties make $CASN:Eu^{2+}$ an eligible phosphor for the use in high color gamut backlighting units and general lighting applications with a high color rendering index. The material however holds the disadvantage that its emission spectrum falls beyond the visible range, meaning that only 75-80% of the emitted light can be perceived by the human eye. The emission spectrum of nitride based phosphors can be tuned by varying activator concentrations. Drawbacks like emission shift even further into the infrared region and concentration quenching have to be considered nonetheless. Its high tolerance towards elevated temperatures in terms of temperature quenching renders CASN:Eu^{2+} to be well suited for the application in high power LED devices. (Khanh et al. 2015, pp. 93-94)

Alkaline earth (M) nitridosilicates, $M_2Si_5N_8$:Eu^{2+} or 2-5-8 nitrides feature fluorescence in the orange to red region what qualifies them for the use in warm white LED devices. Showing a broad excitation band ranging from about 270 nm to 560 nm with peak sensitivity at 400-450 nm, 2-5-8 nitrides prove to be adequate phosphor materials for LED chips emitting in the near UV or blue range of the spectrum. The spectral range of emission can be modified by introducing different concentration of alkaline earth elements to the host lattice. Generally the coveted deep red emission of the compound is accompanied by losses due to the partial location of the emission peak outside the visible spectrum.
2-5-8 nitrides activated with divalent europium show very low thermal quenching under temperatures typical for the operation of high performance LEDs. With emission intensities of 85-91% of the initial room temperature intensity at 160 °C, those compounds are very well applicable. (Khanh et al. 2015, pp. 97-99)

6.2.6 1-2-2-2 Oxynitrides

The family of oxy-nitride phosphors exactly denoted as $MSi_2N_2O_2$:Eu^{2+} or 1-2-2-2 oxy-nitrides hold emission chromaticities bluish to yellowish-green based on the chemical composition of the host crystal. Depending on the alkaline earth metal (M) content the crystal structure alters from monoclinic (M=Ca) to triclinic (M=Sr) or to orthorhombic (M=Ba) what strongly influences the crystal field exerted on the incorporated dopant ions. This changes the characteristics of excitation and emission as well. (Khanh et al. 2015, pp. 99-103)

6.2.7 β-SiAlON

Another class of nitride-based phosphors providing green emission with a small FWHM of about 1690 cm^{-1} featuring a hexagonal crystal structure is represented by the so-called β-SiAlON compounds. They consist of a solid solution of β-Si_3N_4 in which silicone and nitrogen atoms are partially substituted by aluminum and oxygen atoms. Due to limited solubility the compound is confined to $Si_{6-z}Al_zO_zN_{8-z}$ ($0<z<4.2$). The material exhibits a broad absorption spectrum spanning from 300 nm to 500 nm with maxima at 303 nm and 405 nm respectively. The peak of the emission band can be found at 535 nm with a FWHM of about 55 nm. The compounds Stokes shift is estimated to be around 2700 cm^{-1}. β-SiAlON is subject to concentration quenching. The magnitude of the effect and correspondingly the critical Eu^{2+} concentration is determined by the aforementioned *z*-value. In general *z*-values above 1 cause a lower optimal Eu concentration of around 0.3 mol%. For raised *z*-values showing more profound effects of activator concentration on the emission characteristics the emission band can be positioned in the deeper red region by increased Eu^{2+} concentrations. Moreover β-SiAlON possesses very good thermal quenching traits. At temperatures of about 200 °C remaining emission intensities of 15-85% compared to the initial room temperature values can be observed (for $z=1$ and Eu^{2+} concentrations from 1.5 at.% to 0.02 at.%). Because of that, β-SiAlON is suitable for the use in high power LED packages. (Khanh et al. 2015, pp. 103-104)

7 The Principles of Light Perception

The information for the compilation of this chapter were retrieved from technical literature published by Kahle and Frotscher (2001), Ramachandran (1992), Schmidt (1999) and Boyce (2014).

For the description of a light source most likely qualities like brightness and color are applied in daily use. Those two basic properties of light are strongly determined by the working principles of our eyes and parts of the brain that are assigned with the interpretation of optical stimuli. First the way humans perceive brightness is not equally distributed across the visible spectrum of light. Secondly the color of a light source depends on the composition of wavelengths that it includes. Radiometric units and quantities as they are used in physics to describe electromagnetic radiation, be it visible or invisible, lose part of their meaning when it comes to the human visual apparatus. Due to this, the lighting industry established standards by which artificial light sources can be described with respect to the nature of human light perception.

7.1 Anatomy and Physiology of the Human Eye

The human eye is a highly developed sensory organ and can be anatomically described as a direct extension of our brain. During the first month of embryonic development, the eyes of a human begin to emanate from the diencephalon, resulting in a structure, which is directly linked to the visual cortex by the highly clustered optical nerve in a newborn. The eyeball consists of the vitreous body encapsulated by the sclera. This opaque, fibrous protective layer made of connective tissue gives the eyeball its shape and distinctive white color. Other important parts are the transparent cornea, the elastic lens which is partially covered by the iris and the retina clad with millions of photosensitive receptor cells. This is where the actual perception of light takes place. Cornea and lens constitute an optical apparatus with the task of focusing the light that enters the eye in a focal point on the retina. The retina itself shows an extremely high grade of innervation in order to offer the ability to resolve the vast number of stimuli exerted by the photoreceptors. The highly branched nerve fibers get bundled in the blind spot or scotoma where they leave the eyeball as the optic nerve. This is also the place where blood vessels enter to supply the retina with blood. This area completely lacks photoreceptors and thus does not contribute to vision. However there is a compensation mechanism carried out by the visual cortex to interpolate the missing sensory stimuli. The eyeball is attached to various muscles that enable quick and precise movement to allow for tracking of moving objects as well as prevention of receptor saturation. The muscle operated iris works like an aperture in order to adapt to varying intensities of brightness by increasing or decreasing its diameter. (Kahle and Frotscher 2001, pp. 338-359; Ramachandran 1992; Schmidt 1999; Boyce 2014, pp. 43-57.)

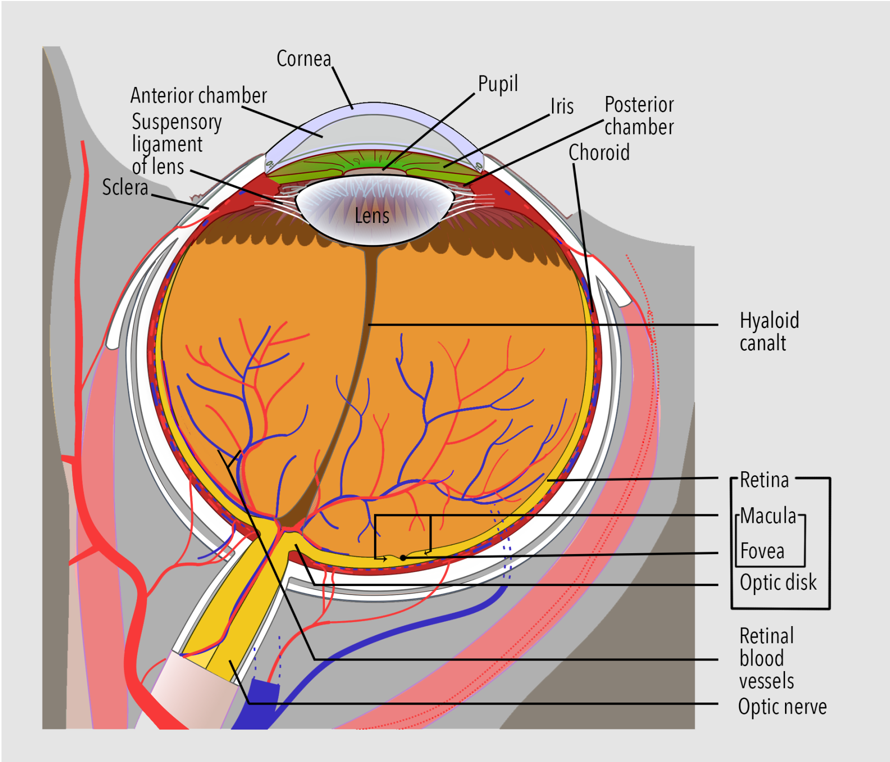
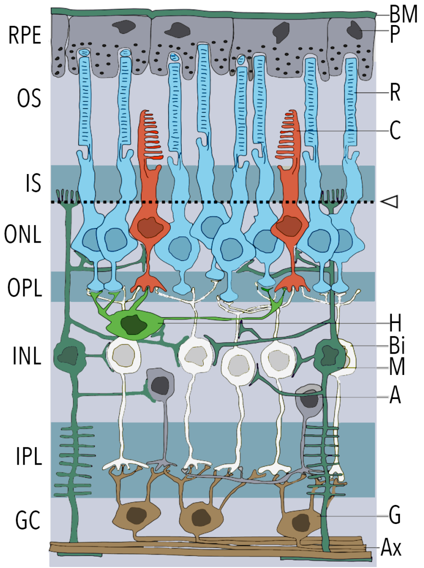


Fig. 21: Anatomic image of the eyeball. (adapted from Castilhos 2007)

Due to the fact that the retina allows humans to discern between a broad spectrum of colors and an even broader spectrum of light intensities it is worthwhile to take a closer look at the working mechanisms in its complex structure. The human eye possesses two types of photoreceptive cells called rods and cones. Rods are responsible for scotopic vision in low light conditions prevalent in twilight or at night times. Although their sensitivity suffices to even detect single photons, by providing information solely about the detected light intensities instead of wavelength distributions they only supply us with an image similar to a black and white photography. With higher levels of brightness, cones begin to respond to light in different wavelength regimes initiating the range of photopic vision. Cones can be subdivided into three different photoreceptor types. S, M, and L type cells differ in their respective wavelength dependent light sensitivities. The abbreviations S, M and L stand for short, medium and long wavelength respectively. This means that the visible spectrum is covered by three different types of receptors each having its excitation maximum in a different range of wavelengths. Translated to the human perception of light, short wavelengths correspond to blue, medium wavelengths to green and long wavelengths to red colors respectively. Cone cells, like the aforementioned rods, only have the ability to determine light intensities but deliver no information about the composition of the radiation exciting them. Subsequent comparison of all three signals in the visual cortex of the human brain then leads to a color impression. Very important for this comparative evaluation of stimuli is the spectral overlap of all three receptor types. Being able to respond to the same wavelength but with a different degree of sensitivity, the different types of cones send a distinctive excitation pattern to the brain. Those signals comprise data about the spectral composition of the light perceived which are also called tristimulus values. This is also the reason, why a combination of two or more different wavelengths can appear to have the same color as light consisting of a single wavelength. In this phenomenon called color metamerism, human vision is not able to discern if a receptor response is caused by photons of a single wavelength or a combination of light all across the visible spectrum. (Khanh et al. 2015, pp.7ff.; Schmidt 1999; Stryer 1987; Schnapf and Baylor 1987; Masland 1987; Boyce 2014, pp. 43-57)

The mechanism of visual phototransduction is the working principle by which light entering the eyeball is converted into electrical signals by rods and cones. Centerpiece of this cascade of chemical reactions is the molecule rhodopsin. It is embedded in the internal bio membranes of photoreceptor cells and consists of two bio molecules: retinal and opsin. As a large complex molecule, opsin serves as a supportive framework for the incorporation of retinal in its internal structure. If a retinal molecule absorbs a photon, it changes its spatial configuration and activates the whole rhodopsin complex. The activated rhodopsin itself now interacts with transducin leading to the substitution of guanosine diphosphate (GDP) in its α-subunit by guanosine triphosphate (GTP). Subsequently the α-subunit separates from the remaining β-γ-complex and suspends the inhibition of the inactive phosphodiesterase by removing its γ-unit. The now active phosphodiesterase starts to break down guanosine monophosphate, a protein that controls Na+ channels in the outer bio membranes of the photoreceptive cells, leading to reduced influx. The membrane of the cell becomes hyperpolarized. To reverse the process and end the hyperpolarization, hydrolysis of GTP to GDP causes the transducin α-unit to reunite with the dormant β-γ-unit. Meanwhile phosphodiesterase and rhodopsin are regenerated. (Schmidt 1999, ; Stryer 1987; Schnapf and Baylor 1987; Masland 1987; Boyce 2014, pp. 43-57)

Hyperpolarization of the outer segments of the cone and rod cells propagates towards the synaptic ending of those cells and induces a change of neurotransmitter concentration between them and the dendrite of an adjacent bipolar cell. As opposed to conventional synaptic junctions where a stimulus is communicated by an abrupt change in polarization leading to a surge of neurotransmitter concentration across the synaptic cleft, photoreceptors convey nerve signals by a continuous reduction of transmitters. By further reducing their moderate negative membrane potential in accordance to the intensity of the received light stimulus they are able to communicate by decrease of transmitter output. After the associated bipolar cells receive the stimulus from the photoreceptors, their axons pass it on to the retinal ganglion cells on the surface of the retina. The ganglion cells themselves integrate the stimuli of multiple bipolar cells to a receptive field and send them as a combined nerve pulse along their axons meeting in the blind spot, finally forming the optic nerve. From there on, the signals reach the optic cortex where they are processed. For details about the involved brain structures as well as the cognitive perception of light, the inclined reader is referred to specialist literature. (Schmidt 1999 ; Stryer 1987; Schnapf and Baylor 1987; Masland 1987; Boyce 2014, pp. 43-57.)



RPE retinal pigment epithelium
OS outer segment photoreceptor cells
IS inner segment photoreceptor cells
ONL outer nuclear layer
OPL outer plexiform layer
INL inner nuclear layer
IPL inner plexiform layer
GC ganglionic cell layer

BM Bruch membrane
P pigment epithelium
R rod
C cone

Arrow
membrana limitans externa

H horizontal cell
Bi bipolar cell
M Müller cell
A amacrine cell
G ganglion cell
Ax axon

Fig. 22: Anatomic image of the human retina. (adapted from Hartmann 2013)

With the discovery of a third receptor type, the understanding of psychological as well as physical impacts of light has advanced considerably. Humans are subject to changes of their bodily and mental conditions during the course of a day. The availability of daylight and its spectral composition during the different times of day act like a clock to our organisms. Even without daylight the human body performs a functional sequence that recurs approximately every 24 hours. This chronology of hormone secretions and other involuntary processes is called circadian rhythm. It is an autonomous and self-sustaining circle. The essential parts of the brain involved in its perpetuation are the nucleus suprachiasmaticus and the pineal gland. The nucleus suprachiasmaticus can be described as an inner master clock that keeps up synchronization between the respective chronologies of metabolic functions. By periodically stimulating the pineal gland to secrete melatonin, a neurohormone that induces phases of rest in the whole human organism, it regulates sleep patterns as well as circadian rhythms. The activity of the nucleus suprachiasmaticus is strongly influenced by daylight, which serves as a synchronizing element. The relatively late discovery of intrinsically photosensitive retinal ganglion cells elucidated how the circadian rhythm is synchronized by exposure to daylight. Those ganglion cells represent a third type of photosensitive receptor within the retina. They use melanopsin, a different photopigment in comparison to rods and cones, to detect light in the blue range of the visible spectrum at 460 to 480 nm. As blue light mostly prevails during the time between dusk and dawn reaching its maximum while the sun rises to its peak, those specific receptors inhibit the activity of the nucleus suprachiasmaticus leading to a decrease in melatonin blood levels. At this time of the day, humans usually feel most capable to perform mental or physical tasks. This insight has decisive consequences for the choice of artificial light sources in both indoor- and outdoor lighting. Mostly for lamps that stay lit during night times, it has to be considered to what extend the wake-sleep rhythms of exposed people are interfered with. This suggests that light sources with high proportions of blue light should be employed with care in order to avoid extensive effects on human sleep cycles. With the availability of light at any given time of the day, especially people of industrialized countries became able to extend their periods of activity far into the night. Since the comprehensive introduction of synthetic light in industrial facilities, shift workers for instance suffer from distortions of their natural biorhythms. Among the symptoms are sleep disorders, lapses in mental focus, listlessness and detachment from social life. (Khanh et al. 2015, pp. 44ff.; Schmidt 1999; Stryer 1987; Schnapf and Baylor 1987; Masland 1987; Boyce 2014, pp. 43ff.; Posch et al. 2010)

7.2 Colorimetry

Looking at direct as well as indirect light sources, the two basic qualities that determine our perception are brightness and color. Due to the fact that perception of light is a psychophysical process based on complex interconnected principles, the impression of both color and brightness is always relative to a combination of outer and inner circumstances. As mentioned before, in order to model those subjective properties with the aim to allow for reliable predictions on the impression of artificial light sources, the distinctive features of human vision have to be taken into consideration. One of the most important properties is the inhomogeneous distribution of light sensitivity across the visible spectrum. In addition to that the trichromatic structure of light perception under daylight conditions and its unique combination of stimuli need to be represented by adequate approximations. This is the reason why constructs like color matching functions and tristimulus values have been introduced. Because it would not be expedient to base the technical description of color on the signal intensities of the different cone types, the color matching functions for a standard calorimetric observer are applied. By taking the varying photoreceptor densities on the retina into account, those functions are subdivided in terms of visual angle. For color stimuli subtending an angle of 1°-4° the CIE 1931 and for angles of 10° the CIE 1964 standard calorimetric observer are recommended respectively. (Khanh et al. 2015, pp. 22ff.; Boyce 2014, pp. 5-28)

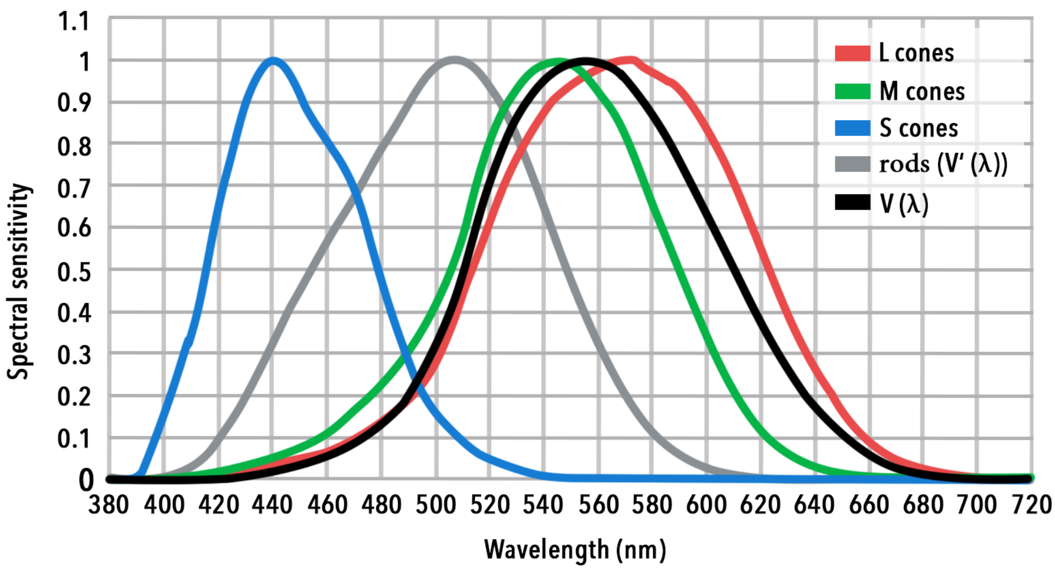


Fig. 23: Spectral sensitivities of human light receptors. Also shown: the luminous efficiency function V (λ). (Khanh et al. 2015)

Color matching functions serve the purpose to make predictions about which spectral radiance distributions evoke the same color impression under reproducible circumstances for a standardized observer. Starting from the spectral distribution of a certain color stimulus provided by a spectroradiometer for instance, the tristimulus values can be determined by using the color matching functions.

$$X = k \int_{360nm}^{830nm} L(\lambda)\bar{x}(\lambda)d\lambda \quad Y = k \int_{360nm}^{830nm} L(\lambda)\bar{y}(\lambda)d\lambda \quad Z = k \int_{360nm}^{830nm} L(\lambda)\bar{z}(\lambda)d\lambda \tag{7.1}$$

In this description L(λ) is the spectral radiance distribution of the color stimulus and k is a constant. For reflecting color samples, the spectral radiance of the stimulus L(λ) corresponds to the spectral reflectance R(λ) of the sample multiplied by the spectral irradiance from the light source casting light on the reflecting sample E(λ). If the sum of the XYZ tristimulus values of two different color stimuli match, humans will not be able to draw a distinction.

The value of k is determined according to

$$k = 100 / \int_{360nm}^{830nm} L(\lambda)\bar{y}(\lambda)d\lambda \tag{7.2}$$

where y(λ) is one of the three color matching functions for the CIE 1931 standard colorimetric observer.
The constant k is set for the tristimulus value of Y to be 100 for ideal white objects with spectral reflectance R(λ)=1 by definition. For historical reasons the color matching function y(λ) equals the luminous efficiency function V (λ) (CIE 1924), therefore the value of k can be set to equal 683 lm/W for self-luminous stimuli. Consequently the value of Y correlates to the luminance of the self-luminous stimulus. According to their significant deviation of color matching functions for stimuli with visual angles exceeding 4° the tristimulus values X10, Y10 and Z10 can be calculated. This means that stimuli perceived in a larger visual angle do not necessarily match with those of narrower ones. In order to represent the three dimensional color space in a clearly arranged manner the so-called chromaticity coordinates have been established:

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z} \tag{7.3}$$

The values of x and y are used to create a diagram of chromaticity coordinates which is called the CIE 1931 chromaticity diagram or the CIE (x,y) chromaticity diagram.

In this diagram color stimuli that can be perceived by the human eye are confined by the horseshoe like shaped spectral locus and the purple line on the bottom of the diagram. White color impressions are located in the middle whereas saturation of primary colors and their respective mixtures increases towards the spectral locus. Color hue (red, green, blue, purple, yellow, cyan) changes around the center region of white tones. (Khanh et al. 2015, pp. 22ff.; Schubert 2006, pp. 292ff.; Boyce 2014, pp. 5-28)

Although the tristimulus values are sufficient to describe color stimuli across the visible range, psychological attributes like lightness, brightness, hue, chroma, saturation or colorfulness cannot be expressed extensively. To address this problem color space or color appearance models have been introduced. They comprise mathematical descriptions especially designed to depict the aforementioned attributes. In the following short explanations about those psychological characteristics of light perception are given:

- *Hue* describes a feature of visual sensation, which leads to the perception of a light stimulus to be very similar to the colors red, green, blue, yellow or a mixture of them.
- *Brightness* refers to the subjective sensation of a color stimulus by which it appears to be more or less intense.
- *Lightness* reflects the impression of brightness a stimulus evokes by comparison to a similarly illuminated reference white. It is also part of the concept of related colors.
- *Colorfulness* refers to the attribute of a color stimulus being perceived to show are more or less chromatic color. It commonly increases with luminance for a given chromaticity.
- *Chroma* represents the perceived colorfulness of the color stimulus relative to the brightness of a white reference light source. This characteristic is mostly observable in lit interiors.
- *Saturation* is the attribute related to the impression of colorfulness of a stimulus compared to the intensity of its own brightness.

Those attributes or features regarding the color perception of a certain color stimulus are not only governed by the stimulus itself but also by the so-called adapted white point. The adapted white point depends on the spectral properties of the surrounding illuminant light. White points can reach from warm white with a noticeable yellowish shade to cool white showing a bluish tint. Changing chromaticities of the prevalent light source exert a strong effect on the color perception of colored objects on grounds of the spectral change of tristimulus produced by the different light source emission spectra. Nevertheless our visual system is able to partially compensate for those spectrally induced changes by chromatic adaption. This mechanism helps to equalize the perception of colors despite the substantial changes of the emission spectra of the light sources illuminating the observed object. This ability however is strongly diminished in the case of monochromatic or quasi-monochromatic light sources, which lack enough spectral variety to create white light. (Khanh et al. 2015, pp. 27ff.)

With respect to the perception of white light, a slightly curved line called the blackbody locus located at the lower middle of the CIE diagram represents the color compositions leading to the impression of a light source to be white. It is deduced from the spectrum emitted by black body radiator. This radiation spectrum, which solely depends on the temperature of an idealized black body, can be described by the Planckian curve. With increasing temperature the maximum of power emitted through electromagnetic radiation shifts towards shorter wavelengths along with an overall increase in blackbody irradiance. This phenomenon can be observed while comparing the yellowish tone of a thermal radiator emitting at a temperature of 2000 K and the bluish tint of the same radiator emitting at 20000 K. Though they are not ideal black bodies, filaments of incandescent lamps fulfill these principles very well. This is the reason why standardized incandescent lamps are used as reference light sources to assess the color rendering capabilities of other light sources. Based on that, the concept of correlated color temperature (CCT; $T_{cp;}$ unit: Kelvin) yields the corresponding temperature of a black body radiator to a light source with an accordant chromaticity. Those daylight illuminants like D65 (T_{cp}=6504 K) and D50 (T_{cp}=5003 K) (Khanh et al. 2015, p. 40; Boyce 2014, pp. 5-28) are commonly used as target white points when it comes to adjusting the spectral radiance distribution of synthetic light sources. (Khanh et al. 2015, p. 40; Boyce 2014, pp. 5-28)

As the following diagram (Fig. 24) shows, blackbody radiators at comparably low temperatures or light sources with low CCTs respectively (e.g. 2700 K) feature large amounts of radiation in the red and yellow color regime and are therefore referred to as warm white illuminants. D50 and D65 for example exhibit larger contents of blue light and for this reason appear to have a bluish tone. Those light sources are referred to as cool white. Nonetheless human perception is subjective leading to the contradictory impression of cooler light to be emitted by actually hotter thermal light sources.

One drawback of the CIE 1931 chromaticity diagram is its non-uniformity. A certain distance in the green portion of the diagram represents a lesser change in the perceived chromaticity than in the region representing red and especially blue chromaticities. To compensate for this shortcoming, the so-called MacAdam ellipses have been introduced. Inside those ellipses, color change is hardly noticeable for the human eye.

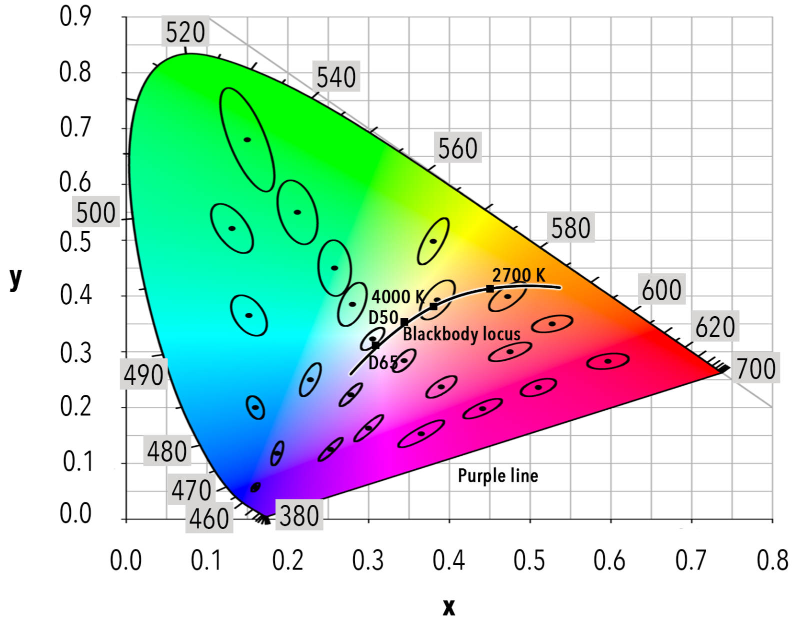


Fig. 24: CIE chromaticity diagram with MacAdam ellipses and black body locus. (Khanh et al. 2015)

In order to create a uniform color space, the axes of the CIE 1931 diagram have been distorted to create the CIE1976 diagram where an equal change in color coordinates creates an equal change in perceived chromaticity. Other even more accurate descriptions are provided by the CIELAB Color Difference and CAM02-UCS Uniform Color Space and Color Difference models respectively. CIELAB uses Euclidean distances to model perceived total color differences including lightness between two color stimuli in a rectangular color space but also shows some remaining non-uniformities in certain areas.

To address this problem, the CAM02-UCS Uniform Color Space and Color Difference model includes an extended set of adjustable parameters. This way it also can be applied to a broad variety of viewing conditions. (Khanh et al. 2015, pp. 32ff.; Schubert 2006, pp. 275ff.; Boyce 2014, pp. 5-28)

7.3 Basic Photometric Units

The production of efficient and applicable light sources strongly depends on the right understanding of the principles on how the human visual system perceives electromagnetic radiation of the visible spectrum. Radiometry as a branch of optics provides a selection techniques to characterize visible as well as invisible radiation in terms of spatial power distribution in a strictly physical way. The use of appropriate detectors is essential to obtain stringent and reproducible results. But regarding our very own light detector, the eye, completely different prerequisites apply. This is where the realm of photometry begins. To elucidate the connection between those two methods and to prevent any confusion the respective definitions taken from the Handbook of Optics are quoted: "Radiometry is the measurement of energy content of electromagnetic radiation fields and the determination of how this energy is transferred from a source, through a medium, and to a detector" Whereas photometry is defined as follows: "The radiation transfer concepts … of photometry are the same as those for radiometry. The exception is that the spectral responsivity of the detector, the human eye, is specially defined. Photometric quantities are related to radiometric quantities via the spectral efficiency functions defined for the photopic and scotopic CIE Standard Observer" (Khanh et al. 2015, pp. 17).

This Standard Observer is described by the two standard luminous efficiency functions. Those are the CIE (1924) photopic V (λ) function for daytime vision and the CIE (1951) scotopic V' (λ) function for nighttime vision. As a consequence, photometry can be considered as a special branch of radiometry tailored to the spectral sensitivity of the human eye. Based on that, the fundamental photometric quantities can be deduced from their radiometric matches. Implementing the V (λ) function leads to the conversion of the respecting quantities. The spectral distribution $X_{e\lambda}$ of a certain radiometric quantity X_e can be converted into the quantity itself when integrated over the range of visible wavelengths between 380 and 780 nm.

$$X_e = \int_{380nm}^{780nm} X_{e\lambda} d\lambda \tag{7.4}$$

To obtain the according photometric quantity X_V, the function $X_{e\lambda}$ is modified by the CIE (1924) photopic luminous efficiency function V(λ). Integration over the visible range yields:

$$X_V = K_m \int X_{e\lambda} \cdot V(\lambda) \cdot d\lambda \tag{7.5}$$

Here, X_V represents a luminous photometric quantity associated with photopic vision, $X_{e\lambda}$ denotes a radiant quantity and K_m stands for the luminous efficacy of radiation (LER) fixed at K_m=683 lm/W. The value of K_m transforms the power of electromagnetic radiation into lumen (lm), an associated photometric unit. With the implementation of the V'(λ) function for night-time vision corresponding scotopic quantities can also be determined. By doing so, the photopic value of K_m also has to be exchanged for its scotopic counterpart K_m=1699 lm/W.

The following section gives an overview over basic radiometric concepts and their photometric analogies. (Khanh et al. 2015, pp. 16-18 ; Schubert 2006, pp. 275-286)

7.3.1 Radiant Power (Radiant Flux) and Luminous Flux

"Radiant power or radiant flux is the power (energy per unit time t) emitted, transferred or received in the form of electromagnetic radiation" (Khanh et al. 2015, p. 12). It is represented by

$$\Phi_e = \int_{380nm}^{780nm} \Phi_{e\lambda} \cdot d\lambda \tag{7.6}$$

The analog photometric quantity is luminous flux as defined by

$$\Phi_V = K_m \int_{380nm}^{780nm} \Phi_{e\lambda} \cdot V(\lambda) \cdot d\lambda \tag{7.7}$$

Both concepts comprise the total power of light emanating from a light source in all directions of space.

7.3.2 Irradiance and Illuminance

Irradiance describes the proportion of radiant power impinging on a certain surface element compared to the area of that element

$$E_e = \frac{d\Phi_e}{dA} \tag{7.8}$$

The analog photometric quantity is called illuminance:

$$E_V = \frac{d\Phi_V}{dA} \tag{7.9}$$

7.3.3 Radiant Intensity and Luminous Intensity

"Radiant intensity is the ratio of the radiant power leaving a source to an element of solid angle propagating in the given direction" (Khanh et al. 2015, pp. 19ff.).

$$I_e = \frac{d\Phi_e}{d\Omega} \tag{7.10}$$

The analogous photometric quantity is called luminous intensity:

$$I_V = \frac{d\Phi_V}{d\Omega} \tag{7.11}$$

7.3.4 Radiance and Luminance

"Radiance is the ratio of the radiant power, at an angle α to the normal of the surface element, to the infinitesimal elements of both projected area (dA cos α) and solid angle (dΩ)" (Khanh et al. 2015, pp. 21ff.).

$$L_e = \frac{d\Phi_e}{d\Omega dA \cos\alpha} \tag{7.12}$$

The analog photometric quantity luminance is defined by:

$$L_V = \frac{d\Phi_V}{d\Omega dA \cos\alpha} \tag{7.13}$$

The concept of radiance and Luminance shows some interesting properties. It is a quantity that strongly depends on anisotropic circumstances as well as the surface properties of real light emitters since they are non-uniform and show spatial extension. Moreover, radiance is closely related to the direction from which it is detected (does not apply for lambertian radiators). It should be mentioned that radiance is of special importance in radiometry since propagation of radiance is the quantity, which is conserved in a lossless optical system. Luminance can be used to represent the image, which is projected on the retina by the human optical system. Therefore, the effective impression of brightness mediated by the signals of retinal photoreceptors caused by a plane shaped light source is determined by its illuminance and not by its total luminous flux (Khanh et al. 2015, pp. 17-22).

Table 3: Radiometric and corresponding photometric units. (Schubert 2006)

Photometric Unit	Dimension	Radiometric Unit	Dimension
Luminous flux	lm	Radiant flux (optical power)	W
Luminous intensity	lm / sr = cd	Radiant intensity	W / sr
Illuminance	lm / m^2 = lux	Irradiance (power density)	W / m^2
Luminance	lm / (sr m^2) = cd/m^2	Radiance	W / (sr m^2)

8 Quality Criteria for Solid State Lighting

In order to assess the performance of a light source in a meaningful manner, different performance parameters have been established. This chapter pays attention to the features, which constitute for both an effective and efficient lighting device. Of course some parameters depend on the respective field of application, but physical qualities like light flux or wall-plug efficiency give unmistakable information about how much of the expended power has been transformed to useable light. Frequently, the terms efficacy and efficiency cause for confusion when it comes to determining the actual output of a LED lamp. Because the sensitivity of the human eye is not homogeneously distributed over the entire spectral range of visible light, it is difficult to quantize the "brightness" of a light source with strictly physical terms. Thus radiometry has to be complemented by photometry allowing for measurements matching the principles of human light perception. (Khanna 2014, p. 19) Information for the following descriptions are taken from technical literature published by Khanh 2015, Khanna 2014, Liu and Luo 2011 and Schubert 2006.

8.1 Efficiency and Efficacy

The efficient transformation of electrical energy within a light-emitting diode is a key aspect for sustainable lighting. As far as mere physical efficiency is concerned, there are some basic terms that are used for representation.

8.1.1 Feeding Efficiency

This term denotes the ratio of the average energy of the photons emitted to the total energy contained in an electron-hole pair created by the power supply of the device:

$$\eta_{feed} = \frac{h\bar{\text{v}}}{qV_F} \tag{8.1}$$

where *h* is Planck`s constant, ν the mean photon frequency, q the elementary charge and V_F the forward voltage drop across the diode. Under ideal conditions such as a perfect crystal lattice and negligibly small electrical resistances high energy electrons comprised in the thermal distribution would cause the crystal to cool. For real semiconductor crystals, which possess an external quantum efficiency (explained below) however, the cooling effect is nullified by internal heating. Also, heating results from electrical resistances of contact areas and leads as well as from serial resistances of the semiconductor layers themselves. The voltage loss (V_F-$h\nu/Q$) can be quantified to about 0.05-1.0 V for small driving currents, resulting in a feeding efficiency of η_{feed} ~0.75-0.97. (Khanna 2014, pp. 221-222; Khanh et al. 2015, pp.60ff.)

8.1.2 External Quantum Efficiency

The value called external quantum efficiency is deduced from the description of internal quantum efficiency. In contrary to the ideal case, where the active region a LED device emits one photon for every electron that has been injected, real LEDs suffer from loss mechanisms. Therefore, the internal quantum efficiency represents the number of photons emitted by the active region divided by the number of electrons injected into the active region.

$$\eta_{int} = \frac{number \quad of \quad photons \quad emitted \quad from \quad active \quad region \quad per \quad second}{number \quad of \quad electrons \quad injected \quad into \quad LED \quad per \quad second} = \frac{\frac{P_{int}}{(hv)}}{\frac{I}{e}} \tag{8.2}$$

Where I is the injection current and P_{int} is the optical power emitted by the active region. If all of the emitted photons can escape into free space, the device has an extraction efficiency of unity. Again, this value will diverge from unity in a real LED due to reabsorption, total internal reflection or other limiting factors (for detailed information see chapter 6).

$$\eta_{extraction} = \frac{number \quad of \quad photons \quad emitted \quad into \quad free \quad space \quad per \quad second}{number \quad of \quad photons \quad emitted \quad from \quad active \quad region \quad per \quad second} = \frac{\frac{P}{(hv)}}{\frac{P_{int}}{(hv)}} \tag{8.3}$$

Here, P is the optical power emitted into free space. The extraction efficiency can heavily impact the performance of LEDs used for lighting, since manufacturing structures with values exceeding 50% necessitates highly advanced and costly production processes. Finally, one can derive the external quantum efficiency from those values as

$$\eta_{ext} = \frac{number \quad of \quad photons \quad emitted \quad into \quad free \quad space \quad per \quad second}{number \quad of \quad electrons \quad injected \quad into \quad LED \quad per \quad second} = \frac{\frac{P}{(hv)}}{\frac{I}{e}} = \eta_{int}\eta_{extraction} \tag{8.4}$$

It describes the number of photons emitted by the device divided by the electrons injected into the device during a discrete time interval. According to Khanna the external quantum efficiency can be represented as the product of three factors: internal quantum efficiency, injection efficiency and light extraction efficiency. (Khanna 2014, p. 222; Schubert 2006, p. 86; Khanh et al. 2015, pp.60ff.)

$$\eta_{ext} = \eta_{int} \cdot \eta_{inj} \cdot \eta_{extr} \tag{8.5}$$

8.1.3 Wall-Plug Efficiency

The wall-plug efficiency or power efficiency is defined as

$$\eta_{power} = \frac{P}{IV} \tag{8.6}$$

It can also be described by the product of external quantum efficiency (η_{ext}) and feeding efficiency (η_{feed}) of the device.

$$\eta_e = \eta_{ext} \cdot \eta_{feed} \tag{8.7}$$

8.1.4 Luminous Efficacy

To determine the luminous efficiency of a light source, the emanated luminous flux is used. As opposed to the radiometric quantity of radiant flux, the luminous flux is characterized by the ability of humans to perceive light giving the subjective value of brightness. (Khanna 2014, p. 28) It is obtained by using the radiometric light power:

$$\Phi_{lum} = 683\frac{lm}{W}\int_\lambda V(\lambda)P(\lambda)d\lambda \tag{8.8}$$

Where $P(\lambda)$ is the power spectral density respectively the light power emitted per unit wavelength and the prefactor 683 lm/W is a normalization factor. Thus the optical power emitted by a light source is

$$P = \int_\lambda P(\lambda)d\lambda \tag{8.9}$$

The luminous efficacy of optical radiation is measured in lumens per watt of optical power. It corresponds to the conversion efficiency from optical power to luminous flux.

$$Luminous \quad efficacy = \frac{\Phi_{lum}}{P} = \frac{683\frac{lm}{W}\int_\lambda V(\lambda)P(\lambda)d\lambda}{\int_\lambda P(\lambda)d\lambda} \tag{8.10}$$

Considering strictly monochromatic light sources where $\Delta\lambda \rightarrow 0$ the luminous efficacy is equal to the eye sensitivity function $V(\lambda)$ multiplied by 683 lm/W. For multicolor light sources and most of all white light sources, the luminous efficacy has to be calculated by integration over all wavelengths. (Schubert 2006, p. 284)

8.1.5 Luminous Efficiency

A quantity, which is also measured in units of lm/W is the luminous efficiency. It is determined by the luminous flux of a light source divided by the electrical input power.

$$Luminous \quad efficiency = \frac{\Phi_{lum}}{IV} \tag{8.11}$$

The luminous efficiency can be converted to a value of luminous efficacy by dividing it by the electrical-to-optical power conversion efficiency. Consequently, for light sources with perfect electrical–to-optical-power conversion the luminous source efficiency equals the luminous efficacy of radiation. (Schubert 2006, p. 285; Khanh et al. 2015, pp. 60ff)

The reason for the introduction of those two quantities has its origin in the human perception of light. It seems appropriate for a source of electromagnetic radiation to specify it by its ratio of power input to power output. This would satisfy the actual definition of efficiency. But when the human eye and its non-homogeneous sensitivity across the visible spectrum of light become involved, it is no longer expedient to talk about efficiency in a strictly physical sense. Luminous efficacy and luminous efficiency both are based on the usage of a prefactor to normalize the relationship between the units Lumen and Watt. Also the unit Lumen is derived from the luminous flux, which is a value tailored to reflect the varying sensitivity of human vision to different wavelengths of light. This fact makes it difficult to compare light sources of different colors as well. Especially with the light of white LEDs containing manifold wavelengths, it is complicated to make meaningful comparisons. Generally, due to highest sensitivities at around 555 nm, the efficacy of any multicolored light source is increased by the presence of high proportions of green light. Efficacy values are moreover influenced by the magnitude of current used to operate the LED. Elevated drive currents decrease the ratio between luminous output and power consumption. Phosphor saturation accompanying the overdriving of LEDs might also worsen this ratio by shifting the emission spectra more towards the blue color regime where light perception by humans is poor. (Khanna 2014, pp. 228-229; Khanh et al. 2015, pp. 16ff.)

8.2 Phosphor Properties

In order to provide efficient LED-based lighting, the use of suitable high quality phosphor materials is indispensable. Decisive qualities like luminous efficiency, color temperature, reliability, color rendering and overall lifetime strongly depend on the used phosphor material. The most important properties for high performance materials are described in the following:

First of all phosphors should exhibit a strong absorption in the emissive wavelength range produced by the LED. In this context a broad spectrum of excitation helps to harness large portions of the light generated by the light-emitting diode. In this case performance impairment caused by variations in emission spectra among LED dies only exerts a mitigated effect. Additionally an adequate emission spectrum of the phosphor itself grants the pursued light characteristics. Those may lie in a broad spectrum for general illumination or a narrow spectrum for LCD backlighting to fit built-in color filters. High quantum efficiencies are very important as well in order to reach high yields of converted light. This quality is strongly influenced by production parameters such as crystallinity, particle size distribution and particle morphology. Another important property is represented by thermal stability. The inclination towards thermal quenching below operating temperatures of the used LED die is strongly detrimental to the overall light output and affects lifetime and chromaticity of the device. Also refined conversion properties help to reduce energy loss for high values or self-absorption for low values of Stokes shift respectively. Both reduce the efficiency of the whole system. Moreover suitable phosphor materials should feature high chemical stability. Especially changing temperatures, irradiation with short-wave light and atmospheric conditions can lead to accelerated degradation. Furthermore the phosphor particles themselves should offer suitable morphology and size (5-20 µm in diameter) to avoid sedimentation during production or increased scattering effects. Since LED devices are produced in large numbers, the employed phosphor materials have to be easily synthesizable and qualified for mass production. Because of large production volumes of most LED illuminants, high phosphor prices do influence cost-effectiveness of the product despite the small amounts of phosphor incorporated into a single LED package. Finally, to reduce health risks and ecological damage, phosphors should not contain hazardous materials. (Khanna 2014, pp. 278ff.; Khanh et al. 2015, pp. 72ff.)

8.3 Optical Properties

One important criterion for the assessment of LED performance is the optical spectrum of emitted light. It allows for an evaluation of the comprised wavelengths of light as well as it gives information about their relative proportions. Since the human eye has different sensitivities for different spectral regions of the visible spectrum, it also contains information about the efficiency of the light source considered. Large ratios of blue light for instance, result in lessened efficiency due to minor sensitivity for short wave light. In reducing the emission of blue light (the actual emission color of the LED die) by conversion to light of yellow to green chromaticity substantial gains in efficacy can be observed. Moreover it is beneficial for efficiency if the optical spectrum consists of a broad area ranging over the visible spectrum. A broad spectrum also positively affects the color rendering capabilities of a light source, which usually suffers in the red region because of low red light content.

An important measure for the quality of light emitted by the LED chip is the full width at half maximum (FWHM) or spectral line half width. It provides information about the purity of the emission color. It is determined by the width of the intensity curve at 50% of the total spectral power or emission intensity. The smaller the value the higher is the degree of monochromaticity for the respective LED die. A small FWHM is desirable in cases where phosphors with rather small excitation spectra are used to convert the emitted light.

In addition to the optical spectrum the color rendering index (CRI) and color correlated temperature are important parameters in identifying light quality in solid-state lighting devices. The CCT is a value given in Kelvin, used to describe the color impression of white light evoked in a human observer looking directly at the light source. It can range from cold white to warm white. The CRI on the other hand is constructed quality characterizing the ability of the light source to reproduce the original colors of illuminated objects in comparison to daylight (For more information see chapter 7).

As no light is emitted from the back LED luminaires exhibit a rather spotlight-like character, therefore the distribution of light gives valid information about their emission characteristics. In most cases the light is emitted from the front and the sides of the LED chip. The emitted light interacts with various components of the device such as phosphor layer, silicone encapsulant and attached lenses on its way out. Thus it undergoes various optical processes changing its path and spatial distribution. The pattern of light distribution commonly takes three different kinds of shape: In a Lambertian pattern the light is mostly directed in a forward direction. The batwing pattern features mostly forward directed light but with a splitting in two maxima at angles of higher angular displacement. Side emitting chips only emit light only from the sides without a forward component. In this respect, the included angle of an LED is employed to characterize the degree of angular emission. It is described by the circular angle, which comprises 90% of the emitted light.

Since the light emission of an LED can be expressed by a cone-like pattern it can be rendered by a quantity called the beam angle (or viewing angle). This angle gives information about the light distribution of the emitted light and the perceived brightness of the LED. It is characterized by 50% of brightness decrease based on the maximum value. Therefore the beam angle expresses the angle between the edges of a cone shaped beam within which the light intensity does not fall below 50%. Low beam angles are typical for spotlight LEDs while broader angles are suitable for larger-area lighting. (Khanna 2014, pp. 229ff.; Liu and Luo 2011, pp. 50ff.)

8.4 Extraction and Light Distribution

Important parameters besides the functionalities of the actual LED die and phosphor are the spatial arrangement and morphology of both. With regard to phosphors, the right location in the LED device is decisive. Generally one discerns between two types of phosphor arrangements: remote phosphors and contact or proximate phosphors. Contact phosphors either do evenly coat the surface of the LED chip or are randomly distributed in the encapsulants in which the chip is embedded. Remote phosphors however are not in direct contact to the semiconductor surface but are placed distantly.

There are different methods to place phosphor materials on light emitting diodes. For contact phosphors possible methods of deposition include needle- or jet-based dispersion, conformal coating using spraying-, electrophoresis-, screen printing-, molding-, or sedimentation techniques or the installation of a premanufactured glass or ceramic phosphor carrier. Remote phosphors can be deposited by spin coating or spraying and various printing processes. Though it is crucial for the final performance of the lighting device, that the LED die is properly aligned inside the package before phosphor deposition to ensure correct angular variation of color.

For certain contact phosphor arrangements (e.g. without integrated DBRs), possible loss rates of up to 50% can occur due to reabsorption of backward photons. Those photons in turn contribute to further chip and package heating what causes additional penalties in overall device efficiency. In this regard remote phosphors offer the advantage of advanced efficiencies as they facilitate the extraction or recovery of backscattered photons. The implementation of optical systems to direct the emitted light flux has proven to be helpful for this form of application (Khanna 2014, pp. 278ff.).

Light extraction from semiconductor crystals is a significant issue in the aim to fabricate high efficiency LED devices. Since solid-state lighting materials hold high refractive indices, trapped light within the semiconductor structure proves to be problematic. If light emanating from the active region hits the surface of the crystal in an angle shallow enough, the effect of total internal reflection takes place. The angle of total internal reflection is given by

$$\alpha_c = \bar{n}_s^{-1} \tag{8.12}$$

where $\bar{n}_s^{-1}$ is the refractive index of the semiconductor and α_c is the critical angle given in radians.

For example, a refractive index of 3.3 results in a critical angle of 17°. This is the reason why most of the emitted light is captured inside the semiconductor where it is lost by substrate absorption and subsequent non-radiative relaxation. In the effort to increase light extraction properties, geometrical shaping of semiconductor dies is an effective measure. Nonetheless most of the shapes that decisively enhance light extraction like spherical or hemispherical dome-like structures emerge to be very unpractical since initial fabrication techniques produce planar structures. Cone-like structures face the same difficulties. A widespread yet inefficient structure is the rectangular parallelepiped. Despite its cost and manufacturing advantages much of the emitted light is lost by at least partial absorption. Cylindrical-shaped LEDs require an additional etching step but feature a circumferential light escape ring replacing the four planar surfaces at the side of a rectangular design.

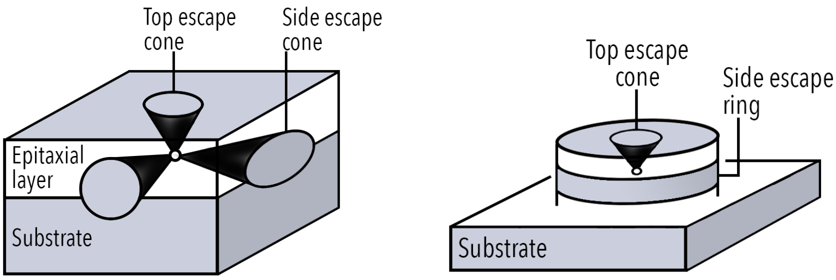


Fig. 25: Geometrical shaping of LED dies.

a) Parallelepipedal rectangular LED featuring a total of six escape cones.

b) Side escape ring and top escape cone in a cylindrical structure. (Schubert 2006)

Designs for high efficiency LEDs commonly exhibit the shape of a pedestal or a truncated inverted pyramid. Those shapes significantly reduce the events of total internal reflections as well as the photon mean paths between them. As a result about half the internal light absorption occurs compared to a conventional rectangular design. However precise die shaping requires increased production expenses.

Textured semiconductor surfaces pose another possibility to enhance extraction efficiency in LED dies. Wet chemical or photoelectrochemical etching of semiconductor surfaces allows for the fabrication of extremely rough surfaces. Rough surfaces substantially increase the probability of a light ray to impinge in an angle below the critical value leading to successful extraction. (Schubert 2006, pp. 150-153; Liu and Luo 2011, pp. 46-47) a)

b)

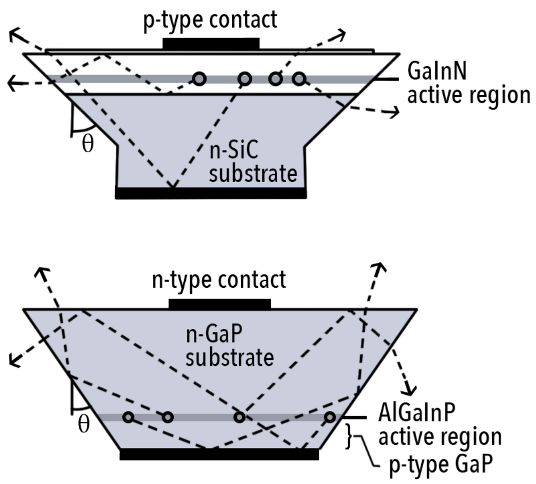


Fig. 26: Light extraction in common LED die designs.

a) Schematic light extraction in a blue GaN die grown on SiC substrate (trade name: Aton).

b) Light extraction in a truncated inverted pyramid made of AlGaInP/GaP. (Schubert 2006)

8.5 Packaging

Packaging of LEDs is one fundamental aspect in creating efficient and long lasting LED light sources. It comprises the connection of the LED chip to the circuit board, the encapsulation and the structures important for thermal management. The quality of the packaging determines how stable the final assembly will be. Important criteria are how resilient the final LED packages encounter stresses like thermal or mechanical shock, aggressive environmental conditions or vibrations. After packaging, LED dies are tested in terms of electrical characteristics and the ratio of operating current to light output. Optical properties such as emission spectra and homogeneity of light emission also determine to which final sales batch the product is allocated. Like mentioned before, thermal management and proper heat dissipation are key aspects. Having very high power densities in comparison to conventional microprocessors, LEDs need elaborated ways of heat dissipation to prevent the components from overheating. Approximately 80% of the power used to operate an LED is transformed to heat. With usual sizes of 350 x 350 µm for 350 mA and 1000 x 1000 µm for 1A chips the current densities reach 285.71 and 100 A/cm^2 respectively. By assuming the forward current to be 3 V this translates to power densities of 857.13 W/cm^2 for a 350 mA LED and 300 W/cm^2 for a 1 A LED. If heat transport away from the die is insufficient, overheating causes for performance and lifetime degradation. Phosphor materials and encapsulants in close vicinity will also take damage. (Khanna 2014 pp. 209-210)

Starting from simple through-hole designs showing two connection pins and a transparent or colored epoxy casing soldered individually into pre-drilled circuit boards, high performance LEDs nowadays employ surface-mounted device (SMT) designs. The chips are mounted directly on the surface of the printed circuit boards using prefabricated contact pads. The advantages are considerable size reduction, reduced production costs and fast manufacturing. Basically the SMT package comprises a base usually made from copper or aluminum, which provides electrical contact and serves as heat sink. The edges are covered by insulating materials to avoid current losses while the upper part exhibits a reflective coating. The underside is plated with gold or silver to alleviate gluing or soldering. Phosphor material for light conversion is added in form of a fine powder incorporated in a polymeric binder on top of the die. The thickness of the light converter varies from a few tens to a hundred microns. To protect the phosphor layer and the underlying chip, an encapsulating layer is applied. A lens encasing the encapsulants in order to enhance light distribution finally covers the whole assembly. Different methods of chip alignment on the heat sink are employed in the manufacturing of LED packages. Using surface mounted technology vertical, lateral and flip chip layouts can be found. (Khanna 2014, pp. 209-219; Liu and Luo 2011, pp. 83-118)

In vertical packaging, the current flows all the way from the whole substrate base of the die to the top. A contact grid on top serves as cathode contact. This setup impairs light output due to the large area covered by nontransparent metal contacts. Zener diodes parallel to the current protect the device from electrostatic discharge. Lateral packaging features both contact areas for anode and cathode on the top-side of the LED die. The soldered on substrate forms an electrically isolating thermal contact to the heat sink. Contact areas and the bonded contact wire obstruct light escape to a certain degree. Those problems do not affect flipped chip packaging. Here, a lateral chip is attached face down on the heat sink, enabling the emitted light to leave without being obstructed by opaque metal contacts. To further reduce light losses by reflection and absorption, the substrate can be removed in an additional manufacturing step at the end of chip production. Improved cost effectiveness in production paired with size benefits is reached by SMT leadless packaging techniques. The chips are contacted over bond wires attached to via structures in the motherboard eliminating any sideways contact structures integrated in the circuit board itself. This saves room normally occupied by contact terminals, which can be used to build large area thermal contacts with increased capabilities for heat transport. Chip on board (COB) technologies add an additional degree of refinement. By enabling LED arrays to be smaller and more closely packed, advantages like high uniformity as well as high intensities of light are accomplished. High thermal efficiency is reached by putting the actual LED die in direct contact with tailored substrate structures and motherboards.

In addition to the methods above, silicon LED packaging represents another technique to maximize heat dissipation as well as efficiency of light extraction. In this wafer-level packaging method adapted from the microchip industry, a silicon carrier with pre-etched cavities and integrated vias is equipped with a flip-chip assembly. After that, the fitting of a phosphor containing encapsulant and an overlying lens cover seals off the cavity. Due to the large number of carriers that can be fabricated on a single silicon wafer, production is easier and less time consuming. Moreover wafer-level packaging enables for better thermal management. In recent times, more manufacturers are transitioning towards various methods of wafer-level assembly due to aforementioned reasons.

As far as heat dissipation and reliability of plastic materials in LED packages are concerned, material degradation is an issue. Seeing that the bigger part of energy expended for the operation of an LED is lost by unwanted heat production, plastic materials have to cope with high power densities and a wide temperature range. Different coefficients of expansion for all the different materials utilized in an LED device lead to internal stresses promoting fatigue or even failure. Results can be microscopic cracks, delamination of plastic layers and chip-mount failure. Thermally induced

breakdown of a bond-wire contact can render an otherwise fully functional device useless. High temperatures exceeding the glass transition temperature of the used plastic materials are to be strictly avoided both during operation and manufacturing. Regarding long-term stability of plastic materials, mainly high levels of humidity in combination with elevated temperatures cause for compromised devices. Most recent materials however, evolved to a stage where improvements have made them resilient to harmful conditions such as withstanding 1000 h of testing in atmospheres of 85° C and 85% relative humidity.
In order to build LED systems with supreme thermal resilience, the printed circuit boards (PCBs) made from FR-4 have to be replaced by more suitable materials. FR-4 is a flame retardant epoxy material reinforced by fiberglass. Although the properties of FR-4 can be enhanced by the incorporation of thermally conductive through holes and metal sheet core layers, metal leadframes, ceramics and silicon prove to be more durable. (Khanna 2014, pp. 209-219; Liu and Luo 2011, pp. 149ff.)

In terms of encapsulants, polymers are the material of choice. They have to provide multiple qualities like high refractive indices, chemical inertness, high-temperature durability and hermeticity. Epoxy resins are used for low to middle power devices emitting in the long-wavelength visible spectrum. Employed in LEDs emitting in the blue or even violet spectrum as well as for applications exceeding 120° C, they start to degrade while losing transparency. To compensate for those shortcomings, silicone encapsulants have been introduced. Silicone remains thermally stable up to temperatures of about 190° C and remains flexible for prolonged periods of time reducing the mechanical stress on the chip assembly. Furthermore, clouding is not as easily introduced as in epoxy resins. Acrylic glass is also used for LED encapsulation, but hinders light extraction due to its relatively low refractive index in the range of 500 – 650 nm.
With the quality of light extraction also depending on the encapsulation, sophisticated designs can help to increase the overall efficiency of LED devices. Several layers of encapsulating material with different refractive indices cause for reduced total internal reflection. The material of highest refractive index is placed next to the LED die followed by layers of lower refractive indices. Mineral diffusers can be utilized to enhance light distribution too. Small particles acting as centers of reflection, scattering and refraction homogenize the pattern of light emission by inducing arbitrary changes of direction in the lights path through the encapsulant. (Schubert 2006, pp. 196-199)

9 Technocentric Approach on Sustainability

With respect to prevalent technological solutions the question arises, whether lighting systems currently in use provide a suitable technical solution for the future. Sustainable lighting technologies are fit to prevail in the face of present and future requirements regarding energy consumption, materials demands and functionality. In practice, technologically persistent light sources are systems that feature high grades of efficiency. Secondly they exhibit a moderate demand for raw materials and functional materials. Lastly they offer light properties, which stand in good agreement with human needs. Any light source which serves those combined purposes in a satisfying manner is able to become a dominant technological solution in the future. In this regard LEDs seem very promising. Therefore a thorough investigation of their capabilities in comparison to conventional technologies is of great interest. The combined assessment of technical properties and soft human factors however necessitates a new term to clarify the considerations in this work.

9.1 Introduction and Derivation of the Concept of Technological Persistency

The term sustainability is used in a broad variety of topics ranging from the management of biological resources (agriculture, silviculture, fishing etc.), over mining to supply chain management. In addition to this multitude of topical contexts its vague use in public discourse led to a blurring of its meaning. In the face of this extensive spectrum of application and conceptual use it is important to clarify the connection in which it is applied (Grunwald and Kopfmüller 2012, pp. 31ff., 107ff., 218ff.). This work is concerned with assessing the sustainability of various lighting technologies. When adapting the concept of sustainability to a technology-based domain it is therefore expedient to dispose of preconceived notions. For this purpose a new term, namely technological persistency, indicating this contextual relationship is introduced.

The term technological persistency is to be understood as a medium with the intention to narrow down all the implied facets of the term sustainability towards the context-related techno-centric approach pursued in this treatise.

Therefore, the aim of the concept of technological persistency is to rearrange the actual core factors of sustainability (economy, environment and society) in a way that facilitates their application on lighting technologies. To establish this analogy to the concept of sustainability, those core-factors are expressed by means of resource strategic considerations (economy), efficient use of energy (environment) and functionality (society).

In this way the concept of sustainability can be adapted to include complex interdependencies on the field of technological innovation and development. Correspondingly, the concept underlying the triangle of sustainability is rededicated to form the triangle of technological persistency. The adaption of the aforementioned core factors is hence to be understood as a way to judge lighting technologies on basis of their ability to persist as relevant technical solutions. The motivation behind this approach is to reach an advancement of possible perspectives on sustainability.

It is intended to extend existing perceptions beyond mere ecological material-related considerations in a manner, which offers the potential to evaluate products of great ecological impact.

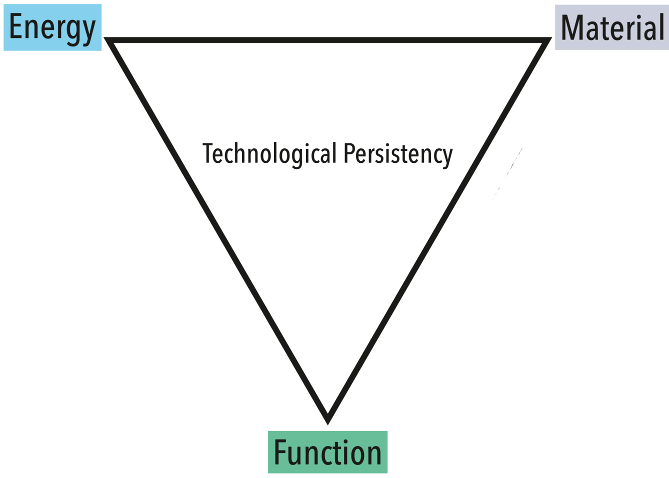


Fig. 27: Triangle of technological persistency. The term technological persistency characterizes a context related, function-specific reinterpretation of the concept of sustainability.

Technological persistency is a concept devised to give information about the qualification of different lighting systems to be sustainable solutions for the years to come. In analogy to the theory of sustainable development the core-factors for technological persistency stand in permanent interaction and feature complex interdependencies. Changes in one sector affect the others and vice versa (v. Hauff 2014, p. 165ff.). Thus the concept of technological persistency also represents a complex system of dynamic interactions, which are involved in the creation of sustainable light sources. It was developed to adapt and augment the concept of sustainability to suit the requirements modern lighting technologies have to face in order to be sustainable. Its goal is to reconcile a revised notion of materials criticality with human factors and extended considerations about energy consumption. Therefore the underlying methodology utilizes a set of core-factors and associated sub-factors in order to conduct an assessment. It aims at providing a sound and up-to-date tool to evaluate the performance of any synthetic light source in terms of technological longevity. Nonetheless it is important to note that this approach is strongly tailored towards the evaluation of lighting technologies and might not be applicable for other subject areas.

9.2 Core Factors of Technological Persistency

The following section gives a descriptive overview over the core factors, which constitute technological persistency. They are chosen on grounds of resource-strategic, technological and functional reasons. They represent important spheres of activity necessary to create sustainable sources of synthetic light. Deduced from significant interests in the domains of economy, environment and society, those core factors form the contextual framework for meaningful assessment. Mentioned interests exert strong influence as external factors on the spheres of energy, material and function.

With regard to the core-factor of energy, the aim to protect the environment by a reduction of global energy consumption and the objective to save non-regenerating energy sources leads to a strive for more efficient illuminants. Provision of Energy and its associated emissions, limited availability of fossil fuels and the controversial climate debate are strong external influences on this topic (European Commission 2012).

The core factor of material is strongly affected by economic circumstances and interests. The requirement to be economically advantageous is one of the basic aspects that determine the handling of material resources and precursors for production. Criticality of raw materials and functional materials as well as their pricing are factors, which are decisive for continued profitable production. Thus the dangers of potential scarcities and finiteness of mineral resources need to be thoroughly considered.

The core-factor of function on its own part is subject to societal influences. Synthetic light sources have to comply with human needs to be viable for the years to come. Moreover it is important to state that human needs are diversified themselves. Different sectors of use feature diverse priorities with regard to functionality and personal preferences cause for a high degree of individuality and variety. This means that there is no lighting solution that fits all requirements, however a multitude of anthropogenic factors decide over suitability of the respective lighting solutions. (Boyce 2014)

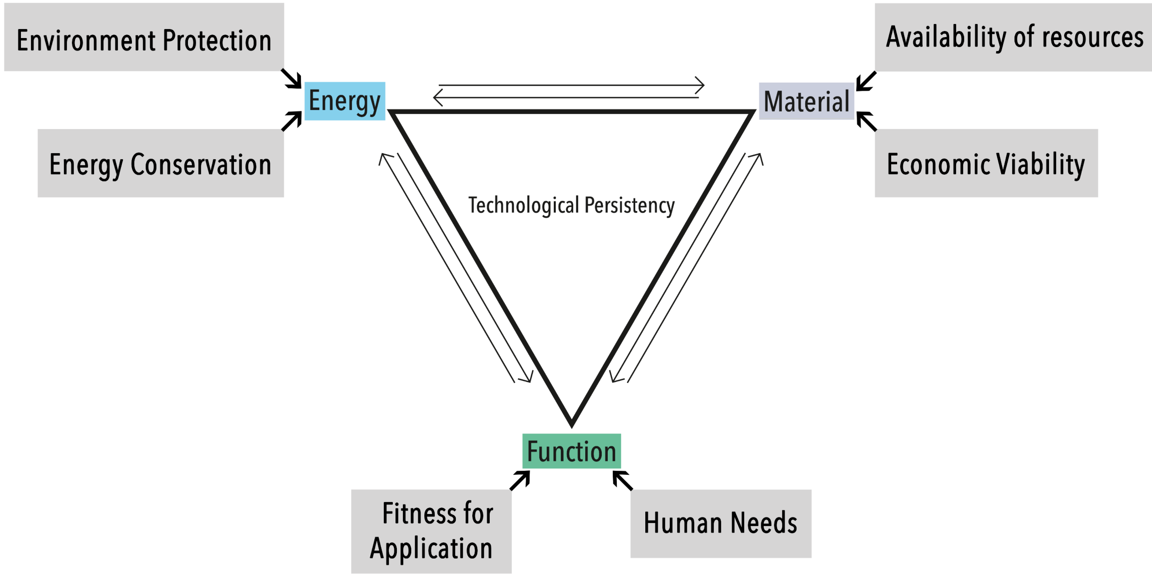


Fig. 28: Triangle of technological persistency with specific external factors exerting influence on each core-factor. Also depicted: Arrows of reciprocal interaction between the core-factors of technological persistency.

9.2.1 Energy

There are great differences among the lighting systems the illumination market has to offer. Corresponding to intended use and technical specifications, a broad range of device efficiencies is observable. Generally it can be found, that the grade of efficiency increases with complexity of both manufacturing methods and technical setup. Elevated degrees of device complexity correlate with increased energy consumption during production. This circumstance has to be considered when judging lighting devices on account of their energy efficiency. By producing lamps that require high amounts of energy during production the time periods after which high in-use efficiencies actually lead to energy savings are elongated. Therefore operational lifetimes play an important role with regard to overall energy efficiency. It is desirable that elevated expenditures inherent to more energy efficient lighting systems are small in comparison to the energy savings achieved during product lifetime. Long periods of time until renewed investment of energy becomes necessary are therefore most advantageous. (OSRAM 2009; DOE 2012; Tähkämo et al. 2014)

9.2.2 Material

Modern lighting devices require a variety of materials in order to be produced. Some of those materials are regarded as critical. As lighting is an application of high volumes, sufficient supply of raw materials is of great interest. Plain assessments of supply risks regarding the raw materials that finally constitute luminaires are not sufficient to represent prevailing circumstances of supply and demand (see Gantner 2016). By incorporating the idea of functional criticality, the significance of value increased materials and the involved fabrication processes gain more relevance. Due to the complex nature of functional materials, supply risks may also arise on grounds of limited production capacities in spite of readily available raw materials. The same principle applies for final assembly. Even if functional compounds do not suffer from shortages, bringing them into the right shape or composing functional components may pose as bottlenecks for supply. Moreover resource efficient implementation of lighting technologies has an impact on materials usage and availability. Sophisticated technical layout of luminaires, minimized losses in production and eased recovery of materials support conservation of resources. Thereby reduced investments in resources contribute to a more sustainable value-added chain.

9.2.3 Function

Light quality is an important functional property of illuminants. Apart from strictly technical requirements, the generated light is dedicated to be perceived by human observers. Hence the characteristics of light emission should be tuned to fit human needs. Light sources that irritate human beings, exhibit poor spectral quality and bad color rendering are to be avoided. In this connection emission spectrum and the color rendering index (CRI) represent measurable qualities. Since the human visual apparatus is adapted to daylight conditions, it is most preferable that synthetic light features close resemblance in terms of spectral distribution. Deviations might cause visual discomfort, disruption of the endocrinal system and unnatural color impressions. In addition to that, illuminants face legal requirements regarding their role as a piece of infrastructure. Standards concerning efficiency, color rendering, content of hazardous materials and end-of-life disposal influence the ability to provide light in a sustainable manner. Therefore the conformity to legal framework is decisive for the applicability of a light source to perform aforementioned tasks. (Khanh et al. 2015; European Union 2003, 2006, 2009a-b, 2010, 2012a-c)

9.3 Identification of Sub-Factors

In order to create a methodology for the assessment of technological persistency, relevant factors for each field of evaluation had to be chosen and put into the right relation. Efficient use of energy, clear-sighted handling of materials and satisfaction of functional requirements are core aspects in the fabrication of lighting devices fit to persist extended phases of technological relevance. In order to preserve the symmetric structure of the triangle of technological persistency each core-factor was subdivided into three subordinate factors. The selection of those factors was carried out on grounds of informative value and empiric conclusion. They are not representative for the whole topical spectrum each core-factor has to offer, but where deemed to be most relevant. On one hand, this deliberate reduction causes omissions, but on the other hand a symmetrical partition with a limited number of evenly distributed sub-factors offers the benefits of manageability. Hence a reproducible clearly arranged basic model of assessment can be implemented. Furthermore, because the chosen factors strongly differ in quality and origin, it seemed appropriate to create a concise breakdown as some of the sub-factors are qualitative in nature whereas others exhibit quantitative characteristics. Also the chosen sub-factors vary in terms of available information and their dependency on subordinate aspects. In the face of those discrepancies regarding scope of information and factual basis adjustments become necessary. Hence the alignment of highly differing factors proves to be a methodical challenge. Details on the coping-strategies for those difficulties as well as their advantages and drawbacks are presented later on.

9.3.1 Energy

Regarding the core-factor energy, *efficacy*, *energy consumption in production* and *durability* provide the basis for assessment. The former two constitute the projected energy demand of a certain illuminant during its life cycle. The latter gives information about the duration of its use phase. Short life cycles result in an additional consumption of energy due to further energetic expenses caused by replacement of defect lighting units. Other factors commonly used for exhaustive life cycle assessments are not considered. It is assumed that they do not significantly contribute to the outcome of an energetic assessment due to their low impact on overall energy consumption of a lighting device. (OSRAM 2009; DOE 2012)

9.3.1.1 Efficacy

Efficacy is an essential part in the evaluation of electric light sources. Basically efficacy is an adapted concept of efficiency that takes the principles of human light perception into account. Efficacy describes the ratio between electrical power input and the radiant flux emitted by a light source within the borders of the visible spectrum. It also includes the respective sensitivities of the eye for different parts of the visible spectral range. Accordingly the quality of a luminaire is strongly based on its capability of transforming electric power into visible light. Nevertheless the term efficiency often is confusingly used to describe light sources with high efficacies in general. In the context of technological persistency, energy savings as a consequence of operating light sources with high efficacies play a fundamental role. They help to reduce energy consumption and henceforth contribute to an overall reduction of the global demand for energy and resources. (For detailed information about efficacy and efficiency see chapter 8)
The sub-factor of luminous efficacy is a strictly quantitative and transferable quality, which is used to describe the efficiency of a given synthetic light source in transforming electrical power to visible light. It is expressed in lm/W (Lumen per Watt) and can be determined for any electrical light source by photometric measurements.

9.3.1.2 Energy Consumption during Production

In the quest for minimization of energy consumption it is expedient to consider the amount of energy that is involved in the production of lighting devices. High demands for energy in production adversely affect the overall efficiency of any lighting technology. Elevated amounts of energy needed to produce efficient light sources, necessitate longer periods of operation to amortize energetic investments. In this respect sustainable provision of lighting devices is also a matter of energy consumption during production. (DOE 2012; OSRAM 2009; Tähkämo et al. 2014)

9.3.1.3 Durability

The use phase of an illuminant decides whether energetic investments and benefits in efficacy can be translated into real energy savings. For short periods of operation, the energy necessary to produce a replacement might exceed the energy savings achieved in comparison to less efficient but more durable light sources. Life cycle assessments conducted by the United States Department of Energy (2012) and OSRAM (2009) showed, that the use phase of illuminants is the most important factor regarding its overall energy efficiency. Consequently durable and efficient light sources pose the most favorable solutions. A lighting technology which necessitates additional input of energy and resources to maintain its operational capabilities over time cannot be regarded as sustainable.

Durability is a quantitative sub-factor, which describes the projected average lifetime of a solid state lighting luminaire. It gives information on how the LED behaves during its phase of use. Presently there are several standards by which life expectancy and degradation of illuminants are specified. Medium life expectancy states, after which period of time 50% of a test group showed total failure. This standard is commonly used for conventional lighting systems such as incandescent and gas discharge lamps. Service life on the other hand indicates, the period of time after which the luminous flux (lm) of an LED has fallen below the initially supplied luminous flux (L50). In recent times, some manufactures use the specifications L70 and L80 which classify an LED to have reached the end of its life when the luminous flux has fallen below 70% or 80% of its initial value. However, depending on personal perception and application, LEDs can deliver light for prolonged time periods beyond this point before they actually fail and need to be replaced. (Baer et al. 2016, pp. 221-224; Lumitronix 2017)

9.3.2 Materials

Regarding the core-factor materials, *criticality of functional materials, raw materials criticality* and *resource efficiency* provide the basis for assessment. Finiteness of natural resources and availability of raw materials are fundamental criteria for the production of commodities. Complex lighting devices such as LEDs or relatively simple constructions like incandescent lamps depend on specific properties of materials and elements. To assess the circumstances under which those resources are handled and if their situation of supply and demand are in a sustainable balance, the chosen sub-factors prove to be suitable. *Raw materials criticality* and *criticality of functional materials* provide an insight into availability of raw materials and functional materials for production. This information can be used to judge the perspective on continued production in the face of estimated increases in demand. *Resource efficiency* is concerned with the usage of those materials in production and technical design. Products that facilitate high output of light under low materials input are highly favorable. The same applies for light sources that show low production losses. Finally recyclability is important for the recovery of functional- and raw materials. Designs that are hard to disassemble or show an extended degree of integration hamper efforts for recycling.

9.3.2.1 Raw Materials Criticality

Long-term availability of raw materials is of great importance with regard to sustaining technological solutions. Most lighting technologies require the distinct properties of materials, which are hardly substitutable. Often those materials exhibit states of elevated criticality. In consequence the number of incorporated raw materials, which are rated to be critical decides over the vulnerability of a lighting technology. Elevated contents of individual critical raw materials add to the risk of supply shortages in production. Accordingly upstream availability of raw materials determines if an extensive use of any lighting technology is feasible. (Reller et al. 2013; Faulstich 2010, p. 6; European Commission 2010)

9.3.2.2 Criticality of Functional Materials

High quality functional materials are essential for the production of advanced lighting devices. Those materials need to be available in high purities. Their production requires sophisticated manufacturing infrastructure and technical know-how. If supply of functional materials is not able to meet the demand associated with a shift towards enhanced lighting technologies, negative effects on the availability of those light sources are to be expected (see chapter 3 or Gantner 2016).

9.3.2.3 Resource Efficiency

Resource efficient implementation of lighting technologies comprises technical layout, minimized losses in production and recyclability. Especially modern lighting technologies exhibit complex designs that incorporate multiple functional components. Therefore quality and arrangement are important factors. A favorable ratio between materials input and luminous output is desirable in order to grant early amortization and sustainable use of resources. Correspondingly production losses pose inhibiting factors for resource efficient manufacturing by unnecessarily increasing materials demand. Finally recycling-friendly layout plays an important role for conservation of resources. Products, which offer quick disassembly and eased retrieval of functional components or even pure materials are highly preferable. In this way most of the contents of end-of-life products can be reused for repeated manufacturing of illuminants or other products. (DOE 2012; Tähkämo et al. 2014)

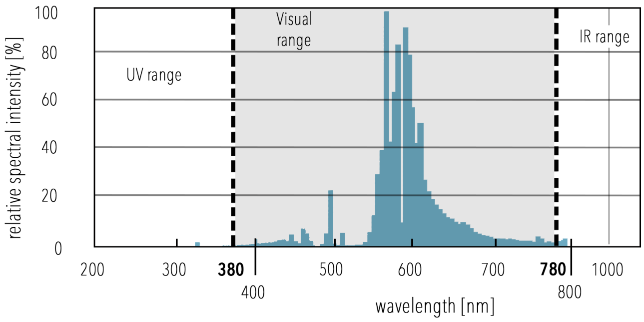
9.3.3 Function

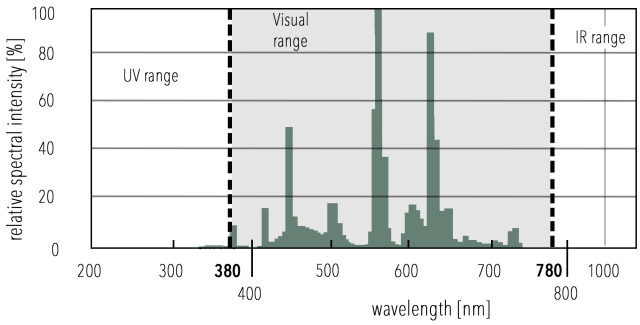
During the evaluation of lighting technologies, human factors are not to be omitted. Compliance to human necessities and the ability to provide appropriate lighting in case of poor natural light conditions are prime requirements. Therefore the core-factor of function is subdivided into *spectral quality*, *color rendering* and *EU legislation conformity*.

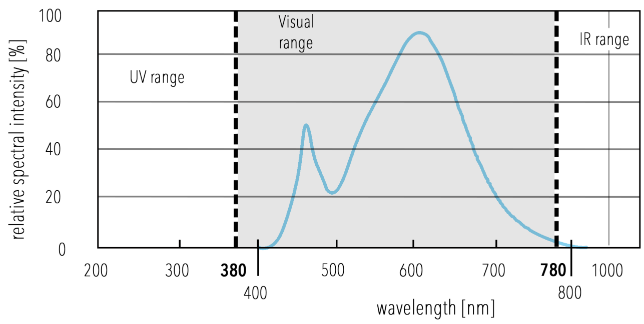
9.3.3.1 Spectral Quality

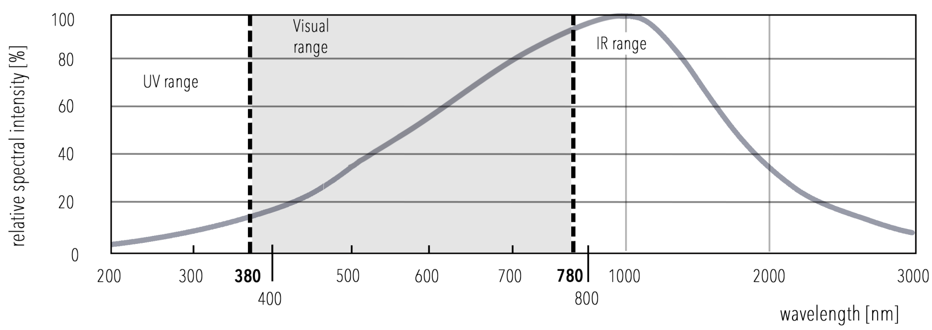
Emission characteristics belong to the prime functional properties of lighting devices. As synthetic light sources are designed to provide light for human observers, their spectral qualities need to comply with the principles of human light perception. The visual apparatus is best adapted to the spectral composition of daylight and its changes during daytimes. Hence illuminants should exhibit spectral properties, which are as similar to daylight as possible in order to be most agreeable. Incandescent lamps for instance exhibit the continuous spectrum of a Planckian radiator similar to that of the evening sun. Fluorescent lamps on the other hand feature a rather spiky spectral distribution, which is strongly discontinuous. Standard phosphor converted LEDs show a spectrum with one narrow peak in the blue region and one broad peak in the yellow region. (Baer et al. 2016, pp. 195-218, 262-265; Boyce 2014, pp. 63-66)

Fig. 29: Spectral distribution patterns of current lighting technologies.
a) High pressure sodium vapor lamp
b) Fluorescent lamp
c) Warm white LED
d) Incandescent lamp (Baer et al.2016)

a)


b)


c)


d)


Poor spectral properties in living- and working environments may cause customers to opt for other technologies. Consequently sustained market presence of a lighting product depends on its appeal to customers and decision-makers (Baer et al. 2016, pp. 400-401).

9.3.3.2 Color Rendering

Depending on the spectral properties of a lighting device its ability to correctly render colors are more or less pronounced in comparison to daylight conditions. The capacity for color reproduction is indicated by the internationally standardized color rendering index (CRI). Good color rendering creates a more complete impression of the visual surroundings. Therefore it is an important functional quality in lighting. (Khanh et al. 2015, pp. 22-39; Schubert 2006, pp. 313-324)

9.3.3.3 EU Legislation Conformity

Legislative measures take decisive influence on the sustained use of lighting solutions. Possible restrictions significantly hamper market availability and thus imply diminishing technological relevance. Legal requirements can have various reasons. For lighting in the EU, the major objective of energy conservation is enforced by respective legal framework advancing the phase out of less efficient technologies. Moreover directives regarding the use of hazardous materials and handling of end-of–life products affect the value added chain of lighting products. Particularly contents of toxic material can mean a criterion of exclusion for market approval. Finally compliance with European law is a crucial factor for the continued relevance of any lighting technology. (McKinsey 2012; European Union 2003, 2006, 2009a-b, 2010, 2012a-c)

9.4 Rating System

The previously described sub-factors are arranged in a fashion that extents the triangle of technological persistency. The existing geometrical layout is expanded to form a nonagonal spider diagram. Here thematically related sub-factors are incorporated into each corner of their superior core factor in order to constitute three new triangles highlighted in color.

To create a visually clear assignment different color themes are chosen for each area. The demarcation between particular thematic fields of evaluation is represented by a gap area rendered in pale grey. The lines connecting the center (of the nonagon) with its edges serve as axes of evaluation in the process of final assessment. Individual performances of the assessed illuminants are represented by coordinates on each sub-factor axis. Interconnecting lines between the points finally span a plane whose size provides information about the overall performance of each technological/technical solution.

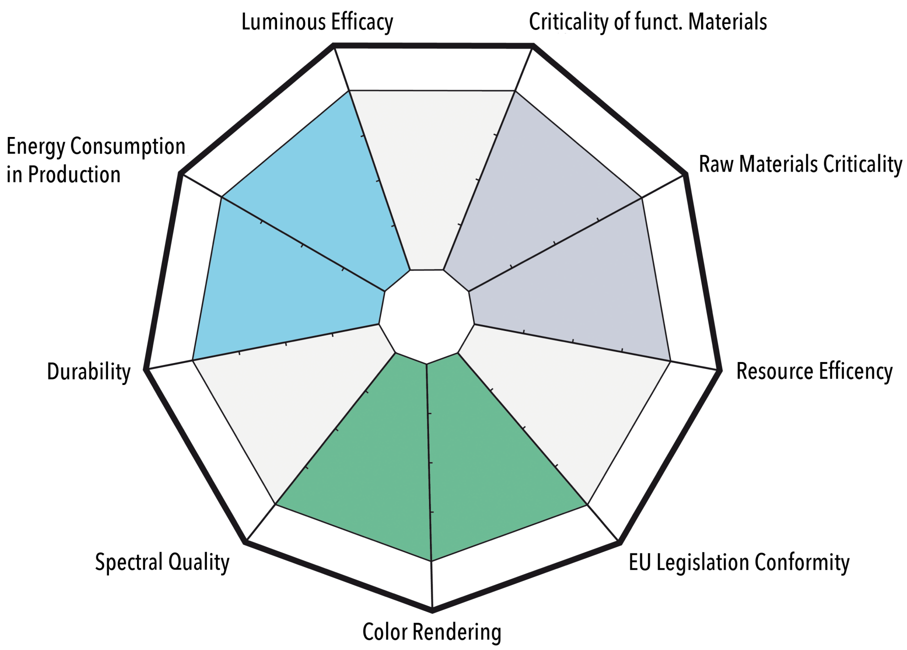


Fig. 30: Nonagonal rating diagram for the assessment of chosen lighting technologies. The sub-factors are thematically assigned to their superior core-factors by color-coordinated areas. Blue represents the core-factor *energy*, green represents *function* and grey represents *material*. Intermediate areas are held in light grey color.

9.5 Discussion of Methodology

Reinterpreting the concept of sustainability with the aim to introduce a more technology-oriented outlook provides the methodical basis for this work. The following section contains information about reasons, challenges and benefits that lead to the devised methodology.

9.5.1 Functional Criticality

Most major publications in the field of resource strategy judge criticality of technologically relevant raw materials in a generalized way. Criticalities of raw materials are determined on the basis of possible reasons for shortages and economic relevance. This method however, does not include the specific circumstances regarding the supply and demand situation for one particular field of technology. The production of functional materials can represent a substantial bottleneck for the production of advanced technical devices. Solid-state lighting for instance is particularly susceptible to those disruptions since it incorporates a variety of functional materials. The necessary production facilities which supply upgraded functional materials for downstream demands are facing challenges in terms of short-term production cycles, high demands on quality and steadily rising production volumes.

The concept of functional criticality takes these circumstances into account. The inclusion of availability of functional materials in the process of determining criticality is one major aspect in the effort to accommodate the specific conditions which apply for the value added chain of lighting products.

9.5.2 The concept of Technological Persistency

This methodical concept represents the intersection where the interests of society, economy and environmental protection (the three core-factors of sustainability) with regard to general lighting meet. Correspondingly it takes the triangle of sustainability to a level of added thematic depth as the core-factors of technological persistency are directly derived from those spheres of activity. Thus they can be adapted to the circumstances under which lighting systems are judged when it comes to determining their sustainability. This approach offers the advantage of technology-specific assessment on the basis of assigned thematically relevant sub-factors. Consequently technological persistency does not contradict sustainability due to its strongly techno-centric focus but supplements it to be applicable for the assessment of lighting technologies.

9.5.3 Schematics for Assessment

The presented nonagonal spider diagram is designed to feature a clearly arranged transparent format. The design reconciles the ability to give a clearly legible overall rating with a transparent representation of the used factors. It infers the geometrical arrangement of the triangle used to describe the core-factors of technological persistency in order to convey associated sub-factors. In this way, the results can be easily taken from the area spanned by the scales of the respective axes. Simultaneously, particular results regarding the individual sub-factors and their proportions among each other stay visible. Hence not only the overall rating and the underlying sub-factors can be displayed but also strengths and weaknesses become evident. Different fields of application such as domestic-, industrial/ commercial-, and public lighting, feature different priorities. Therefore the chosen representation provides a useful tool to determine suitability for application. Apparent fields of high or low performance can be checked against the requirements of respective sectors of application.

9.5.4 Illustration of dynamic Interconnections

This work is able to depict different levels of interaction. On a supreme level, context specific interactions, which are governed by external factors lead to the necessity of sustainable acting and development. On this level, which can be described by a triangle of sustainability based on the three pillars economy, environment and society, permanent reciprocal interactions take place. On a subordinate context specific level the three core factors of technological persistency also stand in constant mutual interaction. Further down on a third level sub-factors of the core factors are also subject to interdependencies and interactions among each other. Important to note in this picture is the fact that aforesaid levels do not only exhibit interactions on a horizontal basis but also feature vertical interdependencies.

The chosen way of description therefore provides detailed insight into a complex nexus of factors and influences. This notion of profound entanglement is fundamental for the assessment approach used in this treatise.

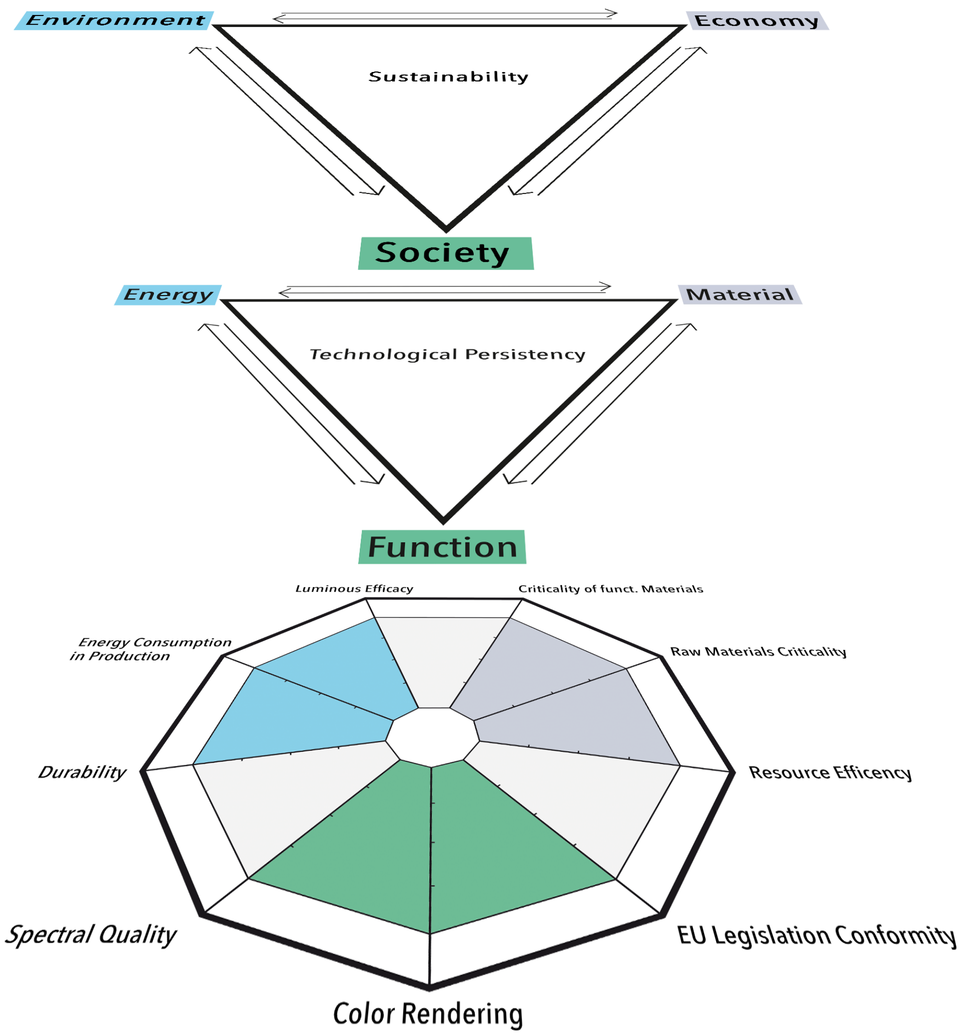


Fig. 31: Nexus of sustainability, technological persistency and applied rating factors

9.5.5 Comparability among different Lighting-Technologies

The methodology of this work is laid out to be applicable to different lighting technologies. Therefore it facilitates the comparison among competing systems. All factors for the evaluation of LED-based luminaires can also be applied for the assessment of conventional light sources. This attribute supplies the context, in which technological persistency represents a relative feature in the face of rivaling lighting options. Comparison of the performances of differing technologies and technical implementations subsequently confers meaning to the attained results.

9.5.6 System Boundaries

The evaluations carried out in this work are extensive and interdisciplinary in nature, therefore it is important to establish clearly defined system boundaries. The underlying data were chosen in a way that provides boundaries regarding time scale as well as informational volume. In terms of time scale, it is of high significance to note that solid-state lighting technology is a field with brief cycles of innovation. Research conducted in the preparation for this work showed that new generations of lamps are introduced to the market in shorter periods of time than it takes to sell existing ones. For this reason the selection of lamps for assessment is to be considered as a snapshot of available technological solutions at the time. Evaluations carried out at a later point of time might meet systems that have made considerable progress in performance. Nonetheless, the selected LED luminaires were chosen with the intention to be as up-to date as possible. In terms of informational volume, attention was given to manageability. In combining criteria stemming from a variety of topics this work faces the challenge of proper alignment. Strictly quantitative factors for evaluation need to be adjusted in order to be used among qualitative factors and vice versa. Far reaching examinations for each factor were avoided in favor of representative and manageable data. Also with regard to the chosen factors themselves a representative selection without a claim to completeness was conducted. The core factors of technological persistency certainly comprise more facets than the sub-factors discussed in this treatise. However relevance and manageability were prime criteria for compilation. This approach led to the omission of aspects that were not deemed to offer any additional informative value but to add unnecessary complexity.

With regard to the spatial scope of this work, the European Union was chosen to provide the boundaries of the considerations made. This decision was taken on grounds of economic importance, status of development and representative size of this area. Especially the legislative measures implemented within the EU are considered to be among the most progressive. Reduction of energy consumption and phase out hazardous or environmentally harmful substances represent prime objectives of policy and are therefore deemed to potentially lead the way for other countries or economic areas.

9.5.7 Scientific Added Value

In combining multidisciplinary aspects to constitute the concept of technological persistency a conventionally mainly ecologic notion of sustainability is augmented towards a systemic approach on technological assessment. It incorporates resource strategic considerations, different facets of energy consumption and human factors. Its informative content extends towards involved interconnections and presents their dynamic relations.

Light sources, which are expected to meet the requirements for prolonged widespread application have to be competitive solutions in order to prevail on a long-term basis. The developed methodology is able to provide a transferable tool for the assessment of illuminants in view of their qualification for sustained application. Moreover it can be used to evaluate existing or new lighting technologies apart from the ones comprised in this work to allow for comparison. Therefore it grants an elaborate instrument for the rating of emerging- as well as established lighting technologies with regard to their future viability.

10 Methodology of Assessment

The following chapter further elaborates the methodology devised for this work. It contains statements about the functional requirements that modern lighting systems have to face when operated in different scenarios of application. Moreover the challenges of alignment regarding the respective sub-factors for assessment and a discussion of the data sources on which they are based are presented.

10.1 Sectors of Application

In order to give a comprehensive overview over the most relevant lighting technologies and their areas of application, a subdivision into sectors of use is conducted. The most important sectors were determined to be domestic lighting, industrial/commercial lighting and public lighting. This selection takes account for the different environments in which illuminants are used and the associated functional requirements. Prioritized qualities and their implementation account for interactions between the core-factors of technological persistency. High performance regarding one of those factors at least results in a tradeoff with one of the remaining two factors and vice versa. More likely, both factors are affected leading to a dynamic interlinked system. The following section gives an overview over the profiles of requirements associated with the three main sectors of use in lighting.

10.1.1 Domestic Lighting

Domestic lighting is subject to the main requirement of providing light, which is suited to create a pleasant environment for living and working. Therefore the core-factor function is of high priority. Highly acceptable illumination in compliance with human needs strongly depends on the sub-factors spectral quality and color rendering. Regarding the core-factor energy, luminous efficacy should be up to date to technological performance standards and pose as an incentive for individuals to opt for energy efficient products. In that sense the benefits of energy saving illumination have to be evident to individual customers. Cost savings as well as personal contribution to the reduction of global energy/resource consumption represent convincing arguments. As lighting devices for domestic applications are mostly in use for a few hours per day, peak performances in terms of efficacy are of moderate importance. Durability however is of high significance. Customer willingness to accept currently high initial cost of energy efficient illuminants in comparison to conventional lighting technologies has to be achieved by elevated lifetimes. With regard to the core-factor material, criticality of functional materials, raw materials criticality and resource efficiency in production are points of importance. Due to high complexity caused by advanced functional requirements, lighting devices for domestic lighting often exhibit increased contents of functional materials. Availability of raw materials, value added functional materials and their efficient use in manufacturing are crucial in view of rising production volumes in the near future. (McKinsey 2012; DOE 2012, European Commission 2012)

10.1.2 Industrial/Commercial Lighting

One of the prime priorities for light sources used in industrial/commercial lighting is high luminous efficacy. Therefore the core-factor energy is of high priority. Since light sources in industrial production experience very long periods of continuous operation and often are deployed in large numbers, reduction of energy consumption and decline in cost of operation represent a desirable goal. Furthermore high degrees of brightness have to be reached in order to provide sufficient illumination for production processes. In this context, high durability also becomes a dominant factor. Extended periods of intense continuous use and large numbers of luminaires necessitate high operational stability. In terms of the core-factor function, compliance to EU legislation and workspace regulations is of great importance. If lighting devices fail to fulfill those criteria, their ability to compete against other lighting technologies is seriously hampered. Factors like spectral quality and color rendering are of increased interest as well. Especially agreeability to the human body is vital for creating pleasant working conditions. Light emission spectra, which adversely affect the human biorhythm, can cause discomfort and illness. In addition, some production processes necessitate good color rendering in order to be practicable. As far as the third core-factor material is concerned, criticality of functional materials, raw materials criticality and resource efficiency in manufacturing represent relevant factors. With respect to solid-state lighting high efficacy and increased durability require refined solutions in terms of chip architecture and quality of functional materials. (Baer et al. 2016, pp. 417-424; Boyce 2014, pp. 287-305)

10.1.3 Public Lighting

Public lighting is expected to be safe and energy-efficient. Because the sector of public lighting contributes a substantial part to the global-overall energy consumption expended for illumination, the core-factor energy is allocated with high priority (European Commission 2012). Due to the fact that most applications, especially street lighting, exhibit prolonged continuous phases of use in demanding environmental conditions, durability is highly important. Extended times of operation, high total numbers of lamps and high output also necessitate economic and ecological viability. Also large numbers, the increased size of illuminants (high luminous output) and energy consumption during production are causing economies of scale. With respect to the core-factor function, compliance to legal guidelines and other standards in public applications is crucial. In terms of light quality, light sources for public lighting face specific demands. Street lighting is intended to provide good vision of nightly surroundings. Because light perception in low light conditions is governed by physiological processes different from those active at brightness-values corresponding to daylight, spectral properties have to be laid out accordingly. Illuminants for street lighting are therefore required to allow for good perception of contrasts and objects instead of featuring high color rendering. Public lighting serves the purpose of furnishing passers-by with a glare-free spatial perception of objects and obstacles. As to the core-aspect material, criticality of raw- as well as functional materials is of particular interest. Large volumes of high output illuminants cause heightened demand for those precursors. (Baer et al. 2016, pp. 425-441; Boyce 2014, pp. 427-450; McKinsey 2012, p. 42)

10.1.4 Summary

In conclusion, apart from differing functional priorities all sectors of use have in common that materials criticality can be a criterion for exclusion with regard to sustained use of any lighting technology or solution. Also non-conformity to legal framework renders continued application impossible. Moreover economic efficiency and environmental compatibility pose prerequisites to be viable options for each sector of use.

10.2 Scaling of Sub-Factors

The chosen sub-factors for evaluation strongly differ in terms of qualitative and quantitative characteristics. Hence the scaling of the axes in the previously introduced nonagonal assessment diagram is designed to accommodate those differences. Respective performances of evaluated lighting systems are divided into five discrete values for all qualitative factors. Qualitative factors like *spectral quality* for example are rendered by markers ranging from low over mid to high. Here a fivefold subdivision allows for the depiction of intermediate values such as low to mid and mid to high respectively. Only the sub-factor *EU legislation conformity* poses an exception to this nomenclature in using a scaling ranging from not available (n.a.) over limited to full conformity (intermediate markers remain in place). The scaling of each axis is normalised to the the characteristics featured by the best performing systems with regard to the considered sector of use.
In contrast quantitative factors such as *efficacy* are reproduced in a detailed manner by numerical indication of data. Here the best performing products for each sector of use provide the maximum value of each scaling. In order to provide a visually consistent image the axes are fitted with five evenly distanced markings (alike those used for the indication of qualitative factors).
However two of the qualitative sub-factors, which are part of the core factor materials are not subject to standardization with regard to best performers. *Criticality of functional materials* and *raw materials criticality* are factors, which apply regardless of considered sector of use. This work regards criticality to be a factual condition that is applicable without being treated as a relative quality. Lighting products that require critical materials for production are subjected to external risks irrespective of the performances of competing illuminants.
The conducted adjustments are introduced with the aim to provide manageability necessary to combine qualitative and quantitative factors in a reproducible and illustrative manner. By standardizing the assessment diagrams applied for the individual sectors of use the comparative character inherent to the concept of technological persistency is taken into account. The qualification for sustained application of any lighting technology is to be seen as relative. The viability of solutions can only be judged in relation to the functional properties of competing options. The absence of alternatives leads to the inevitable establishment of a prevailing lighting system as a dominant concept. In this case the only limiting factors for application are non-maintainable investments necessary for production and operation.

10.2.1 Luminous Efficacy

The scaling of the sub-factor *luminous efficacy* is standardized to the best performing product for each sector of use. In domestic lighting the lamps chosen for assessment show a maximum value of 134 lm/W. Considered illuminants for industrial/commercial lighting exhibit a best performing system with 150 lm/W. The maximum value for lighting solutions in public use is 125 lm/W. All scales reach from zero to the respective maximum values while the intermediate marks are adapted to fit a quadripartite scale.

10.2.2 Energy Consumption during Production

As exact information about the energy expenses involved in the production of each illuminant included in this work is not available (see section on data quality for more information), the results for this factor are based on qualitative estimates. For the sectors domestic lighting and industrial/commercial lighting, the assessment is standardized to the standard incandescent lamp as best performing system. For public lighting the scale is standardized to a high pressure sodium vapor street lamp.

10.2.3 Durability

The scales of this quantitative sub-factor are standardized to the best performing systems in each sector of use. For domestic use the scale spans from zero to 25.000 hours of operation. In industrial/commercial lighting the maximum value is set to 50.000 hours of operation. The maximal value of the best performing system in public lighting is 100.000 hours of operation.

10.2.4 Criticality of Functional Materials and Raw Materials Criticality

The fivefold scales for this qualitative sub-factors reach from low to high. No standardization to a best performer is conducted for each sector of use. Criticality of materials is regarded to be an externally influenced quality regardless of sector of use or technology.

10.2.5 Resource Efficiency

For domestic lighting the scale of assessment is standardized to the standard incandescent lamp as best performer. With regard to industrial/commercial lighting a standardization to the best performing fluorescent tube (Philips Master TL-D ECO) in this sector of use is applied. The scale for public lighting is standardized to a high pressure sodium vapor case lamp.

10.2.6 Spectral Quality

For all three sectors of use the scale is standardized to the continuous emission spectrum of a thermal emitter such as a standard incandescent lamp. For this qualitative assessment factor the deviation from those light emission patterns lead to a decline of results.

10.2.7 Color Rendering

Standardization of the scales for domestic lighting and industrial/commercial lighting is determined by the performance of a standard incandescent lamp. It reaches the maximum possible value of 100 with regard to color rendering index (CRI). In public lighting the scale is standardized to the best performing system. This LED street lamp reaches a CRI of 80.

10.2.8 EU Legislation Conformity

The scales for all three sectors of use are standardized to full compliance to EU legislation. The lowest possible value is set to be non-conform meaning a complete ban on production and sale of an assessed illuminant within the European Union.

10.3 Discussion of Data Sources

10.3.1 Luminous Efficacy

In the European Union the values of luminous flux (output) and wattage have to be indicated on the packaging of every retail lamp while the value is allocated to its corresponding energy class. Energy classes are meant to be a tool to assists consumers in their buying decision by providing information about the in-use energy efficiency of electrical devices. The classes are defined by certain threshold values determined by the European Union (2010). For the assessment of light sources, the relevant data was taken from retail packaging and product data sheets issued by the respective manufacturers. The attained data was not verified by experimental methods in the course of this work.

10.3.2 Energy Consumption in Production

The cumulative energy demand (CED) for the production of illuminants represents suitable information in order to determine the quantities of energy involved in their production. However detailed data specific for individual light sources is difficult to attain. The research conducted for this treatise led to two significant life cycle assessment (LCA) studies. Those sources contain assessments of luminaires for domestic lighting. One study was conducted by the lamp manufacturer OSRAM in 2009 with the objective to assess own products with regard to energy consumption in production and operation. Included illuminants are an incandescent lamp, a halogen spotlight, a compact fluorescent lamp and an LED retrofit lamp. Also the study gives information about the environmental impacts of the included lamps (OSRAM 2009). A second more up-to-date study was conducted by the United States Department of Energy with the title "Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products" in 2012. It uses previously published studies on LCA of different lighting technologies in order to perform a comprehensive LCA assessment of incandescent lamps, compact fluorescent lamps and retrofit LED lamps. This study investigates lamps, which were up-to-date at that time but also incorporates a projection on how LEDs are going to perform in 2015. The projected technical specifications for 2015 LED lighting were found to be in good accordance with the current specifications of LED retrofit lamps. In lack of other significant studies, which provide a comparable level of detail, in-depth consideration and topicality, the DOE-study was chosen to provide the guideline for the assessment of energy consumption in production. However, this study relies on possibly outdated information with regard to the underlying studies. Furthermore, the authors make clear that many of the data used for compilation are based on assumptions made on grounds of benevolently provided information of manufacturers and experts.

Finally it has to be noted that the energy expenses both studies state to be necessary for the production of the considered luminaires considerably differ from each other. The findings of the study conducted by OSRAM lie significantly above the results obtained by the DOE (2012) (see table below).

Table 4: Cumulated energy demand for the production of current lighting technologies. (DOE 2012; OSRAM 2009)

	Standart Incandescent Lamp	Halogen Incandescent Lamp	Compact Flourescent Lamp	LED Retrofit Lamp
U.S. Department of Energy	0.372 MJ	n.a.	3.13 MJ	5.0 MJ
OSRAM	2.2 MJ	5.5 MJ	14.69 MJ	35,64 MJ

On one hand this might be due to the fact that fabrication processes especially for LED lamps have made progress in the period of time between the publications of those studies. On the other hand the results also differ by one order of magnitude with regard to incandescent light bulbs. Incandescent lighting is a mature technology, which is assumed to not have been subject to noteworthy improvements in fabrication in the 21st century. The studies however coincide with regard to CEDs of different technologies in relation to each other: Incandescent lamps are determined to feature a comparably low CED while compact fluorescent lamps show intermediate values and LED lamps were classified to feature the highest energy consumption during production. This leads to the conclusion that a possible reason for quantitative discrepancies lies within the application of different system boundaries. The DOE study gives a very detailed overview over the circumstances under which its result were compiled. The study conducted by OSRAM in turn does not provide such detailed information but refers to the use of the ISO standards 14040 and 14044 for life cycle assessment (OSRAM (e)).

Due to those uncertainties this work refrains from the use of quantitative data for the assessment of energy consumption in production. Furthermore especially the multitude of technical implementations in domestic solid-state lighting poses an additional issue. Both studies assess a single retrofit LED bulb that only represents one possible technical solution. Instead, this work takes a qualitative approach on assessment that is based on the joint results of those studies. Mainly supported by the comprehensive statements of the DOE study, the LED illuminants included in this work are rated on an individual basis. In particular with respect to conventional lighting technologies (incandescent, gas discharge) the findings of the OSRAM study were used to complement the development of results.

10.3.3 Durability

For the evaluation of systems for domestic lighting the specifications on durability (lamp lifetime) stated on retail packaging and technical data sheets are used. The figures are given in hours of operation according to the Commission Regulation of the European Union regarding Ecodesign requirements for directional lamps, light emitting diode lamps and related equipment: "`lamp lifetime` means the period of operating time after which the fraction of the total number of lamps which continue to operate corresponds to the lamp survival factor of the lamp under defined conditions and switching frequency. For LED lamps, lamp lifetime means the operating time between the start of their use and the moment when only 50 % of the total number of lamps survive or when the average lumen maintenance of the batch falls below 70 % whichever occurs first" (European Union 2012b).

10.3.4 Spectral Quality

For the predominant number of cases in which data about the spectral distribution of an illuminant were not available, the emission spectra were taken from technical literature. In this way, it was possible to make statements about the spectral properties of a luminaire based on its technical working principles. Though in lack of precision, this assumption-based approach ensured comparability to other luminaires included in this assessment. Since the sub-factor *spectral quality* is of qualitative nature, potential small deviations of the real product from the general specifications in literature were determined to be insignificant. Otherwise diagrams containing the spectral distribution of light sources were taken from product data sheets issued by the respective manufacturers or the results of independent testing. Last-mentioned results originate from an online source named Fastvoice-Blog. The author (Wolfgang Messer) of this webpage occupies himself with testing and comparing relevant LED light sources with the aim to provide sound customer advice. In the course of those assessments, professional photometry laboratories are employed to conduct measurements. The resulting test protocols are subsequently made available on fastvoice.net. (e.g. Messer 2015a-b)

It has to be noted, neither emission spectra provided by manufacturers nor the data issued on fastvoice.net contain any information on measurement errors. Though as mentioned before, the qualitative nature of the assessment factor itself renders smaller deviations insignificant.

Generally it was observed that emission spectra of the included LEDs, except for one LED tube made by Philips, were not publicly accessible during the time the research for this work was conducted. None of the manufacturers of the included devices issued data on spectral properties. Hence estimates based on technical literature as well as data provided by aforementioned online sources constitute the basis for assessment.

10.3.5 Color Rendering

Data on the color-rendering index of the evaluated lamps was taken from different sources. For domestic light sources the retail packaging of respective lamps was used. Regarding illuminants for industrial/commercial lighting and light sources for public lighting, product data sheets of the respective manufacturers were used to compile information about their color-rendering properties. In most cases it was not possible to check the given specifications on their accuracy. However the comparison to online accessible findings of professional photometry laboratories proved to be in good accordance to the used manufacturer specifications (for more information about data from mentioned laboratories see previous section on spectral quality).

Apart from the fact that the CRI issued by the Commission Internationale de l'Éclairage (CIE) is a broadly accepted standard it has to be pointed out that some experts as well as manufacturers do not see it fit to reflect the actual color rendering capacities of LEDs. Ohno and Davis (2010) of the National Institute of Standards and Technology proposed a new metric called the Color Quality Scale (CQS). It is claimed to maintain consistency with the CRI results of traditional light sources but also to better acknowledge the light rendering properties of modern narrow band LED lights. Instead of using eight pastel colors the CQS uses 15 colors. Incorporating more saturated color tones like deep reds as well as a color preference index (reflecting human preference for more saturated colors) the CQS is assumed to augment the limitations of the widely adopted CRI. One example being that light sources of the same CRI do not necessarily render colors in a reproducible manner. Also insufficient consideration of the effect of color correlated temperature on color rendering proves to be problematic (especially for reddish low CCT sources). (Boyce 2014; Ohno and Davis 2010)

10.3.6 EU Legislation Conformity

Commercially sold light sources are subject to official standards and regulations regarding their characteristics. Many areas of use require the compliance to those standards in order to reach approval for application. The respective catalogues of DIN-Norms and ISO-Norms on lighting are not publicly accessible though. In lack of exact specifications issued in internationally acknowledged standards a legislation based approach was chosen instead. This practice stands in good accordance with the concept of technological persistency as it contains information about the phase out of lighting technologies. Correspondingly, light sources that are banned or soon to be banned by legislation cannot be considered as persistent solutions. Regulations implemented by the European Union, specify basic characteristics that light sources have to hold in order to be approved for retail. Ecodesign lighting product regulations such as EC No 244/2009 (non-directional household lighting), EC No 245/2009 (tertiary sector lighting), EU No 874/2012 (energy labeling for lighting products) and EU No 1194/2012 (directional lighting and LEDs) supply the basis for assessment. In addition to that, directives issued by the European Union with the objective to minimize or restrict the use of hazardous and ecologically harmful substances are also included. Included regulations are EC No 1907/2006 (Registration, Evaluation, Authorisation and Restriction of Chemicals - REACH), EC No 2002/95/EC (Restriction of Hazardous Substances Directive - RoHS) and 2012/19/EU (Waste of Electrical and Electronic Equipment - WEEE).

Examination of the products under assessment in this work with regard to those directives allows for projections about the possible phase out of luminaires containing any hazardous materials like mercury. (European Union 2003, 2006, 2009a-b, 2010, 2012a-c)

10.3.7 Raw Materials Criticality

The studies on raw materials criticality used to provide the underlying data for assessment are "Critical Raw Materials for the EU" published by the European Commission in 2014 and "Materials critical to the Energy Industry" released by Zepf et al. in 2014. The reasons for the choice of those studies are the following: Materials criticality is subject to numerous studies which have been carried out between the year 2008 and today. As has been demonstrated by Gantner (2016), those studies feature a close methodological relation among each other. Often they were compiled under the participation of the same authors or build on previously established methodology. Due to this reason, the two studies mentioned above were assumed to be sufficient with regard to content and independent authoring (Gantner 2016). Both comprise all relevant materials involved in the production of solid-state lighting systems and traditional lighting technologies.

Furthermore the underlying data for raw materials criticality assessment in this work is complemented by a study published 2016 by the Deutsche Rohstoffagentur (DERA) named "Rohstoffe für Zukunftstechnologien 2016". This study contains statements on market trends and future demands of raw materials regarding the manufacturing of white LED appliances.

It has to be noted that the first two sources described do not comprise industry specific assessments. Levels of elevated criticality are assigned to raw materials like indium, gallium and rare earth elements on the basis of large economic relationships. In the EU study, the made considerations are scaled to the whole economic area of the European Union whereas Zepf et al. make their assessments regarding a whole sector of globally acting industry. Only the last-mentioned source (DERA) makes statements based on industry specific circumstances. Here vulnerable supply situations, implied by the European Commission and Zepf et al., are put into perspective. The study presents estimates about the shares of the solid-state lighting industry with regard to annual global demand for indium and gallium. According to the stated figures raw materials demand for the production of LEDs had a marginal share of the global annual demand for indium and gallium.

Moreover the statements on raw materials criticality used as basis for the assessments in this work might not be fully applicable to the solid-state lighting industry due to geographic reasons. Since most of the production plants are located within Southeast Asia, criticality factors with respect to the European Union might not be applicable or mitigated for this region of the world. (LEDinside 2014a-b, 2015a-b, 2016, 2017a-b)

10.3.8 Criticality of Functional Materials

Data availability for this sub-factor proved to be scarce and fragmentary. The technical literature used for this work did not provide suitable information. Hence the only basis of information is supplied by online sources. The prime source of information is a website called LEDinside (www.ledinside.com), which is the online presence of a research division being part of TrendForce. TrendForce is a company that provides market intelligence for high-tech industries. Also the homepage of YOLE Développement, a consulting company performing market research and technology analysis, was retrieved. Both offer comprehensive market reports about the solid-state lighting industry. However the availability of those reports is fee-based. Since four digit Dollar prices for the purchase of those reports exceeded the academic budged, information was gathered from publicly available executive summaries of those reports (cf. Wise Guy Reports 2017 and TrendForce 2017 Membership). Therefore the cited sources do not provide any quantitative data but merely depict industry trends. Research also led to the assumption that public availability of exact numbers on production capacities is not in the interest of manufacturers since those details are regarded as an important asset in a competitive industrial sector.

In view of the fact that the underlying data for evaluation only reflects trends in the industry and lighting market, it becomes evident that the factor itself is only suitable to offer a qualitative overview rather than giving precise rendition of prevailing circumstances. Moreover the availability of a limited number of sources poses a substantial drawback with regard to data reliability. This issue is underlined by the circumstance that information attained from executive summaries cannot be verified due to lack of references.

The quoted market reports issued by TrendForce and YOLE are mainly concerned with the market situation regarding solid-state lighting specific functional materials. They contain statements on availability and production of materials such as wafers, epitaxial growth substrates, LED dies and packages. Data about phosphors are not included. The subsequent search for any indication of criticality of phosphor materials remained inconclusive. No indication for critical supply situations regarding phosphors utilized in LED appliances or mercury-based gas discharge lamps was found. This led to the assumption that criticality is presently not an issue with regard to phosphor supply. This statement is supplied by the fact that according to McKinsey (2012) LED packages are currently experiencing a production capacity ramp up and general price decay. (LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015)

10.3.9 Resource Efficiency

The underlying data for the evaluation of *resource efficiency in production* are deduced from the technical literature on solid-state lighting also used for the theoretical part of this work. Data about the exact consumption of material and production losses could not be attained. Therefore the assessment of this sub-factor is based on qualitative estimates. A tripartite study carried out by the United States Department of Energy (2012) provides a detailed reproduction of the processes involved in the manufacturing of LED illuminants. Those statements and the information contained in a study conducted by Deutsche Rohstoffagentur (2016) regarding production losses in LED manufacturing and resource efficiency in luminaire production supply the basis of assessment.

With regard to traditional lighting systems the time frame in which the research for this treatise was executed did not deliver useful data. This is the reason why it resorts to estimates made on basis of other industrial processes which utilize similar material compositions. Mostly this method is applied for the production of glass for bulbs and metals for contacts and casing. Solid-state lighting devices on the other hand necessitate complex production processes, which allows for losses of material in three main steps of production. Of substrate production, LED die fabrication and packaged LED assembly the two former mentioned steps prove to be especially prone to exhibit production losses. (Deutsche Rohstoffagentur 2016; U.S. Department of Energy 2012)

In addition especially with regard to LED devices a merely observation-based criterion is employed. Illuminants were disassembled when feasible in order to check on their basic structure. The incorporation of an increased number of light-emitting diodes and elevated quantities of phosphor were assumed to contribute to an inefficient use of resources. Lamps, which delivered the same light output while using less light emitting material were considered to be more resource efficient. The same principle applies for LED light sources, which could not be obtained during the phase of research due to financial or logistic reasons. In this case pictures, drawings and data sheets were used to estimate the amount of built-in light emitting structures.

Moreover the process of disassembly was evaluated with regard to recycling-friendly construction. Technical layouts that facilitated easy extraction of functional components for reuse or subsequent recovery of precious raw materials were considered to be more favorable in terms of resource efficiency.

In conclusion the sub-factor *resource efficiency* exhibits methodological challenges in terms of data comparability. Strongly differing production processes impede a comparison among traditional light sources and systems based on light-emitting diodes (Boyce 2014). Furthermore various forms of technical implementation in LED illuminants add complexity to discerning between advantageous constructions and less favorable solutions. Moreover lack of meaningful data and data availability necessitates the use of estimates. Due to this circumstances, this factor cannot be claimed to be comprehensive. Nevertheless it is suited to give an overview over basic production processes and to point out shortcomings in technical implementation.

11 Selection of Solid-State-Lighting Systems for Assessment

The following chapter offers an overview regarding the reasons for the selection of lighting systems and technologies that are included in the final assessment of this work. It gives a detailed information about the most relevant types of illuminants for each sector of use and the reasons for their selection. The remarks are concluded with notes on possible overlaps of application between the sectors of use considered in this work.

11.1 Selection Criteria

Light sources for domestic, industrial/commercial and public use are available in a multitude of shapes, sizes and technical layouts. With the objective to make well-founded statements about the technological persistency of modern lighting systems for the mentioned areas of application, a selection of both relevant and representative technological solutions was required.

- One of the most important criteria in this respect is market presence. Substantial impacts can only be expected when economies of scale start to apply. High volumes of production and success in terms of customer adoption are important prerequisites to contribute to sustained application.
- Lighting technologies of significance need to feature a certain technological relevance. Obsolete constructions that still hold a considerable market share, but are soon to be replaced by already emerging newer concepts, are not to be taken into consideration. Sustainable solutions that are deemed to be in use for extended periods of time however, exhibit the necessary relevance for assessment.
- In order to achieve a substantial ecologic impact, high luminous efficacies play a fundamental role. On the other hand, not all illuminants of significant market presence feature peak efficacies but attract consumers with light quality or competitive pricing.
- Light sources with highly favorable price-performance ratios or outstanding functional qualities have to be considered.
- Apart from application-dependent functional requirements, durability is also a crucial criterion. Devices prone to failure have to be replaced more frequently. Therefore low life expectancies have detrimental consequences for the collective resource demand of the lighting industry.
- Devices featuring only comparably mediocre durability but large sales figures on grounds of other qualities are not to be overlooked in order to perform a representative selection.

11.2 Lighting Systems and their Specifications

11.2.1 Domestic Lighting

LED appliances for domestic lighting include a variety of technical solutions. The market is dominated by retrofit devices intended for replacement of conventional light sources mounted to different kinds of standardized sockets. The prevailing socket types are Edison screw bases in different diameters and bi-pin connectors in varying sizes. Edison screw bases are used to accommodate conventional light bulb designs, although those designs can differ strongly regarding their technical layout and shape. These layouts include: LED filament bulbs, single-chip/multi-chip systems with and without optics for better light distribution and controllable multi-color red-green-blue arrays. Bi-pin connectors are used for mounts of spotlights with narrow beam angles such as in recessed lighting and table lamps. Fixtures integrating solid-state lighting into their design and technical layout are in an initial phase of establishment. They have the advantage of better utilization of the characteristics LEDs have to offer (Khanna 2014). The fact that those fixtures are often inseparably connected to the light emitting diodes causes for high replacement cost in an event of failure. Light generation itself follows different technical concepts for domestic applications. Generally one distinguishes between wavelength converted LEDs utilizing phosphors and multi-color LED arrays (red, green and blue) utilizing chips of different chromaticities to create white light. Multi-color LED arrays furthermore have the ability to render colors different from white by individually mixing light intensities of red, green and blue. In this way, high quality products are able to create light colors spanning the whole visible spectrum. Those lamps are highly versatile and are used to create atmospheric lighting corresponding to daytime or user preference. Phosphor based LED lamps do not feature this variability but have to be chosen according to the desired light properties. They are available in a broad range of color-correlated temperatures, light output figures and color rendering indices. Dimmability is also optional and requires for advanced electrical driver units in comparison to standard LED lamps. In order to provide lamps that suit the aesthetics of old fixtures without lampshades, filament LED bulbs have been introduced. Instead of featuring one or multiple rectangular chips topped by phosphor material they are equipped with multiple ribbon-like light emitting diode structures completely covered in phosphor. As LED lighting devices for domestic use are primarily designed to create a pleasant atmosphere for living and working at home, qualities like color rendering and CCT often outweigh the demand for peak performances in terms of efficacy.

11.2.1.1 Retrofit Bulbs

In order to perform a representative choice in LED light bulbs for assessment, the current range of products available in German hardware stores and electric shops was used as a point of reference. This procedure grants the aforementioned product relevance by availability to a broad group of buyers and the associated economics of scale. Usually LED lamps are categorized by the wattage of an incandescent lamp of equivalent light output. This serves the purpose to provide customers with information about the brightness of the LED lamp at hand using an established easy to understand unit of measure.

Shelves in stores are often subdivided in classes of wattage-equivalents featuring 15W, 25W, 40W, 60W and 100W. The packaging of the lamps gives more information about the actual device-wattage and its incandescent equivalent.
For the assessment in this work, LED retrofit bulbs with light outputs in step with actual practice for domestic applications have been chosen. This means lamps with light outputs corresponding to a 60 Watt incandescent light bulb. According to higher efficiencies of solid-state lighting those numbers currently relate to actual operational wattages from 6 to 9 Watt. Two frosted bulbs of different manufacturers have been chosen for assessment. A lamp called LED STAR CLASSIC A manufactured by OSRAM and a product named High Line LED made by Xavax. Both lamps exhibit a similar technical layout with multiple phosphor coated LED chips enclosed by a frosted plastic cup for homogeneous light distribution. The difference between them lies in their capability for color rendering. The OSRAM lamp features a CRI of 80 whereas the Xavax bulb offers an elevated value of 90. The reason for this selection was the goal to demonstrate the influence of increased light quality on the efficacy of actual light sources for domestic use.
For the evaluation of increasingly popular (according to products on offer) LED filament lamps a product called LED RETROFIT CLASSIC manufactured by OSRAM was included. It features a luminous output corresponding to that of a 60 W incandescent light bulb. Its actual operating wattage lies at 6 W.

11.2.1.2 Spotlights

Another class of retrofit lamps is represented by bi-pin spotlights. They are designed to fit sockets in spotlight fixtures or table lamps. According to this purpose those lamps feature narrow beam angles utilizing the already cone-like emission patterns of single or multiple LED dies. A characteristic which can be further intensified by the use of reflector cups or the utilization of optics. In contrast to bulb shaped retrofit offerings, those lamps are only available in lower wattages. The bandwidth of low power to high-power units ranges from wattage equivalents of 20 W to 50 W with respect to halogen incandescent spotlights. Those numbers relate to actual operational wattages of currently about 2,6W and 4,3W respectively. Two different products have been chosen for the evaluation of LED-Spotlights. One belongs to a product line called LED STAR PAR16 manufactured by OSRAM. Their incandescent wattage equivalents specified with 50W realized by an operational wattage of 4,3W. The other spotlight is a lamp offered by VOLTOLUX reaching a wattage equivalent of 50 W with an operational wattage of 5 W. In contrast to OSRAM which is regarded as a premium manufacturer of LED luminaires, VOLTOLUX is a budget-oriented house brand of the German hardware chain store BAUHAUS. This selection is intended to reveal possible discrepancies between premium and budget products in terms of functional qualities and materials usage.

11.2.1.3 Multi-Color Arrays

Research in electric shops, hardware stores and internet retailing entailed the selection of a system called HUE manufactured by Philips. Its functional properties made for the assumption that this system is regarded to be the most versatile and technically sophisticated at the time. It offers freely configurable color composition embedded in an Internet of Things approach. After installing an interface (called Bridge) which provides wireless connection of individual lamps with a smartphone app via residential internet connection one or several lamps can be individually controlled. Dimmable operation includes full color control (16 million colors) and preprogrammed light situations reaching from mood lighting to daytime adjusted lighting. Furthermore installed illuminants allow for synchronization with music and movies. Lamps are available as conventional Edison screw socket bulbs, spotlights, completely integrated light fixtures and LED light strips. In order to grant comparability to the other systems chosen for evaluation, the Edison screw socket version was selected. This design shows the highest compatibility to already existing light fixtures in European homes and is the most easy to install. (Philips 2017, fastvoice 2017)

11.2.1.4 Conventional Light Sources

In order to provide comparability, existing conventional systems for domestic lighting are taken as reference to the chosen LED luminaires. Therefore a standard screw socket incandescent lamp and a standard halogen incandescent spotlight are included (60 W and 50 W of wattage respectively) in order to illustrate the progress lighting has made in terms of energy efficiency. Moreover their performance in terms of resource consumption and light emission provide a good reference point regarding the challenges solid-state lighting still has to face. In addition a compact fluorescent lamp (OSRAM DULUX SUPERSTAR) with a wattage-equivalent of 60 W and warm-white light emission is added to the evaluation. CFLs represent the strongest competition for LED devices in domestic lighting. They reach significantly higher grades of efficiency in comparison to incandescent lamps, which are now extensively banned by EU-legislation. This means apart from diminishing numbers of incandescent options, customers mainly get to choose between CFLs and LEDs. Despite their technological maturity and acceptable light output, compact fluorescent lamps suffer from inbuilt drawbacks such as content of toxic mercury, lack of mechanical robustness and noticeable starting-times. Most of all mercury content poses to be a fundamental problem in case of accidentally broken lamps and waste disposal. (McKinsey 2012; Khanna 2014, p. 41)

11.2.2 Industrial/Commercial Lighting

Before the advent of solid-state lighting, illumination for industrial and business purposes was dominated by fluorescent tubes. As those concepts are still widely used and contribute a considerable part to the overall energy consumption of industrial and commercial illumination, they are included in this assessment (McKinsey 2012). In this way the performance of LED-based lighting can be evaluated with reference to established technologies. Tubular LED lamps are designed in order to replace fluorescent tubes by adopting respective fixture standards. Their basic layout incorporates a linear alignment of numerous phosphor-coated LED dies housed by a clear or frosted tube made of glass or transparent plastics. LED tube lamps are available in all common lengths featuring various levels of light output. In order to grant a representative selection of available versions low- medium- and high power solutions of different manufacturers have been chosen. Variations in length do not affect the basic technical layout of either technology. To ensure manageability as well as representativeness the chosen devices all feature a length of 1200 mm and similar outputs of luminous flux. (OSRAM 2017, Philips 2017)

11.2.2.1 LED Tubes

To illustrate the current variety in luminaire performance one low-priced tube and one high priced lamp of similar wattage have been chosen for assessment. Former being manufactured by Philips named CorePro LEDtube and the latter produced by OSRAM named Substitube Advanced. Both are designed to fit G13 sockets and are operated using a blind ballast.

11.2.2.2 Fluorescent Tubes

The fluorescent tubes chosen for assessment are both manufactured by Philips. One model named Master TL-D De Luxe features improved color rendering while the model named Master TL-D Eco offers increased luminous efficacy. Both products are designed for the use in industrial environments or commercial settings like super markets.

11.2.3 Public Lighting – Street Lights

To facilitate a representative selection of light sources for street lighting an expert consultation was conducted. The head of lighting department of the civil engineering office in Augsburg, Germany has been consulted with respect to street lighting solutions in the city area. According to Mr. Furnier the city of Augsburg currently uses an extensive stock of various high pressure sodium vapor lamps for street lighting. Those lamps are operated on basis of an intelligent lighting control plan with the objective of energy conservation. Yet wherever new installations are set up, LED street lamps are implemented. One of the products of choice is the Luma series manufactured by Philips. Based on that information two light sources have been chosen for assessment. One middle powered Philips Luma Micro street lamp and one case lamp equipped with a double arch high pressure sodium vapor burner. Similar luminous flux grants comparability of both lamps.

11.3 Reasons for Selection and Limiting Factors

The intention behind the choice in illuminants for assessment was to feature the most relevant solutions up-to-date while accepting potential shortcomings in terms of market coverage. As a result the assessments conducted in this work are to be regarded as rather exemplary instead of comprehensive for all technological modifications in existence. This is also a consequence of the necessity to find a balance between the volume of assessed products and topicality in a fast changing field of technology. Extensive evaluation of all product lines manufactured by companies with considerable market share would not be feasible while simultaneously keeping up with the latest developments. During the phase of research preceding the process of final selection it became obvious that short cycles of innovation play an important role in shaping the supply situation in retailing. Obviously updated versions of a single product enter the market faster than it takes to sell previous ones. Different stages of development regarding single products could be found being simultaneously on offer in the same shop shelves.

Furthermore the choice in correlated color temperature was influenced by cultural reasons. In Germany products for domestic lighting are predominantly sold in warm white versions due the local demand situation. Color correlated temperatures of 2700K to 3000K are most popular in countries of middle and northern Europe (Stefani 2013). With respect to industrial/commercial lighting, color correlated temperatures of 4000 K have been chosen on grounds of their favorable properties in areas of increased human activity (see chapter 7). The selection of color correlated temperature for public LED lighting was deduced from real life conditions in the city of Augsburg.

Finally it is to be noted that possible omissions in terms of relevant products can be compensated by subsequent inclusion of illuminants. The applied methodology for assessment is designed to be applicable to a broad variety of solid-state lighting systems and emerging technologies. Follow-up investigations with an updated selection of illuminants can therefore refer to a previously established methodical framework.

11.4 Application Overlap for Different Sectors of Use

It is worth noting that some of the lamps assigned to single sectors of use in this work are also applicable in other sectors. One overlap in application is represented by the use of spotlights. In addition to domestic purposes, spotlights are also used in commercial lighting. They provide highlights in retail areas or window displays. Moreover fluorescent lamps or LED tubes can be applied in domestic lighting and street lighting as well. Bearing those overlaps of application in mind, one can also use the outcome of the assessments made in this work as a tool to determine the qualification of certain lighting systems for sustained use in other sectors as the here specified.

12 Concluding Assessment

This chapter presents the results of the assessments carried out in the course of this work. The included illuminants are categorized by sector of use and technical working principle. First the results achieved by illuminants for domestic lighting, then the results of lighting systems for industrial/commercial applications and finally the findings regarding lamps for public lighting are presented.

12.1 Domestic Lighting

The following table shows the specifications and order of appearance of the products included in the assessment of light sources for domestic lighting.

Table 5: Considered light sources for domestic lighting

	OSRAM Standard Glühlampe 60W	VOLTOLUX HALOGEN 350lm 50W	OSRAM DULUX SUPERSTAR	OSRAM LED RETROFIT CLASSIC A 60	OSRAM LED STAR ClASSIC A 60	Xavax High Line LED 9,2W	VOLTOLUX LED 390lm 5W 120°	OSRAM LED STAR PAR16 50 36° GU10	Philips Hue White Color and Ambience
Design	Standard Incandescent clear	Halogen Spotlight	CFL	LED Filament	Frosted Bulb	Frosted Bulb	Spotlight	Spotlight	Frosted Bulb
Wattage Equivalent	n.a.	n.a.	60 W	60 W	60 W	60 W	n.a.	50 W	n.a.
Wattage	60 W	50 W	14 W	6 W	8 W	9,2 W	5 W	4,3 W	9 W
Output	710 lm	350 lm	740 lm	806 lm	806 lm	806 lm	390 lm	350 lm	342 - 806 lm
Efficacy	12 lm/W	7 lm/W	52,9 lm/W	134,3 lm/W	100,6 lm/W	87,6 lm/W	78 lm/W	81,4 lm/W	38 - 89,6 lm/W
CCT	2700 K	2800 K	2500 K	2700 K	2700 K	2700 K	3000 K	2700 K	2000 - 6500 K
CRI	100	100	≥ 80	80	80	90	≥ 80	80	> 80 @ 2000 - 4000 K
Durability [h]	1000 h	2000 h	10000 h	15000 h	15000 h	25000 h	25000 h	15000 h	25000 h
Cycles	25000	> 50000	10000	100000	100000	40000	≥ 12,500	100000	n.a.
Temperature range	n.a.	n.a.	0° to 50° C	–20° to 40°	25°	n.a.	n.a.	–20° to 40°	0° to 40°
Socket	E27	GU10	E27	E27	E27	E27	GU10	GU10	E27
Beam Angle	n.a.	n.a.	n.a.	n.a.	n.a.	240°	120°	36°	160° ± 20°
Energy Class	E	D	A	A++	A+	A+	A+	A+	n.a.
Price	n.a.	2,49 €	9,39 €	8,95 €	5,39 €	6,99 €	5,95 €	7,95 €	44 €
Origin	France	Germany	Germany	China	Germany	n.a.	n.a.	Germany	n.a.

12.1.1 Standard Incandescent Bulb OSRAM 60W clear

With about 12 lm/W the standard incandescent lamp features the second lowest *luminous efficacy* of all lamps evaluated for the sector of domestic lighting. The principle of thermal light emission by a tungsten filament does not allow for higher values without substantial penalties in terms of already limited durability (Baer et al. 2016). With regard to *energy consumption in production* the standard incandescent lamp exhibits the lowest value of energy involved in its production process. According to LCA studies conducted by the DOE (2012) and OSRAM (2009) it was determined to be the luminaire, which necessitates the least amount of energy for its production. With respect to *durability*, this type of lamp only offers an average use phase of 1000 hours before it fails completely. This value is at the far low end of the scale. Data on luminous efficacy and durability was retrieved from retail packaging.

Concerning *spectral quality* of light emission, the continuous spectrum of a glowing tungsten filament offers characteristics, which are in closest resemblance to daylight. Due to those spectral properties, the incandescent lamp features a color-rendering index (CRI) of 100 (Baer et al. 2016). In terms of *EU legislation conformity* the standard incandescent lamp is subject to a ban, which only allows the sale of remainder of stock and lamps for special applications other than domestic lighting (European Union 2009a) (EC No 244/2009). This restriction excludes the further use of standard incandescent lamps for general lighting applications in the European Union.

Considering *resource efficiency*, the standard incandescent lamp reaches the highest rating in this evaluation. In comparison to compact fluorescent lamps (CFL with integrated ballast) and LED lamps this technology incorporates the least amount of material (lowest overall weight), the least complex technical layout and is composed of the smallest number of chemical elements. Due to the simple technical layout of incandescent lamps their basic contents of glass and metal are easy to separate. They can be obtained in rather pure fractions as basis for further recycling processes. As to *raw materials criticality* the standard incandescent lamp shows the lowest degree of criticality among all lamps assessed. Tungsten (glow filament) is considered to be critical by the publications used as basis of information for this thesis. With regard to *criticality of functional materials* the standard incandescent bulb was, according to the definition of functional materials used in this work, determined to be free of such materials. No complex compositions specifically designed and produced for the manufacturing of luminaires are incorporated. Glass, metal socket, connecting material and glow filament are either made of materials that are used in large quantities in a variety of industrial processes or consist of slight modifications of those materials. (European Commission 2014; Zepf et al. 2014; OSRAM 2007)

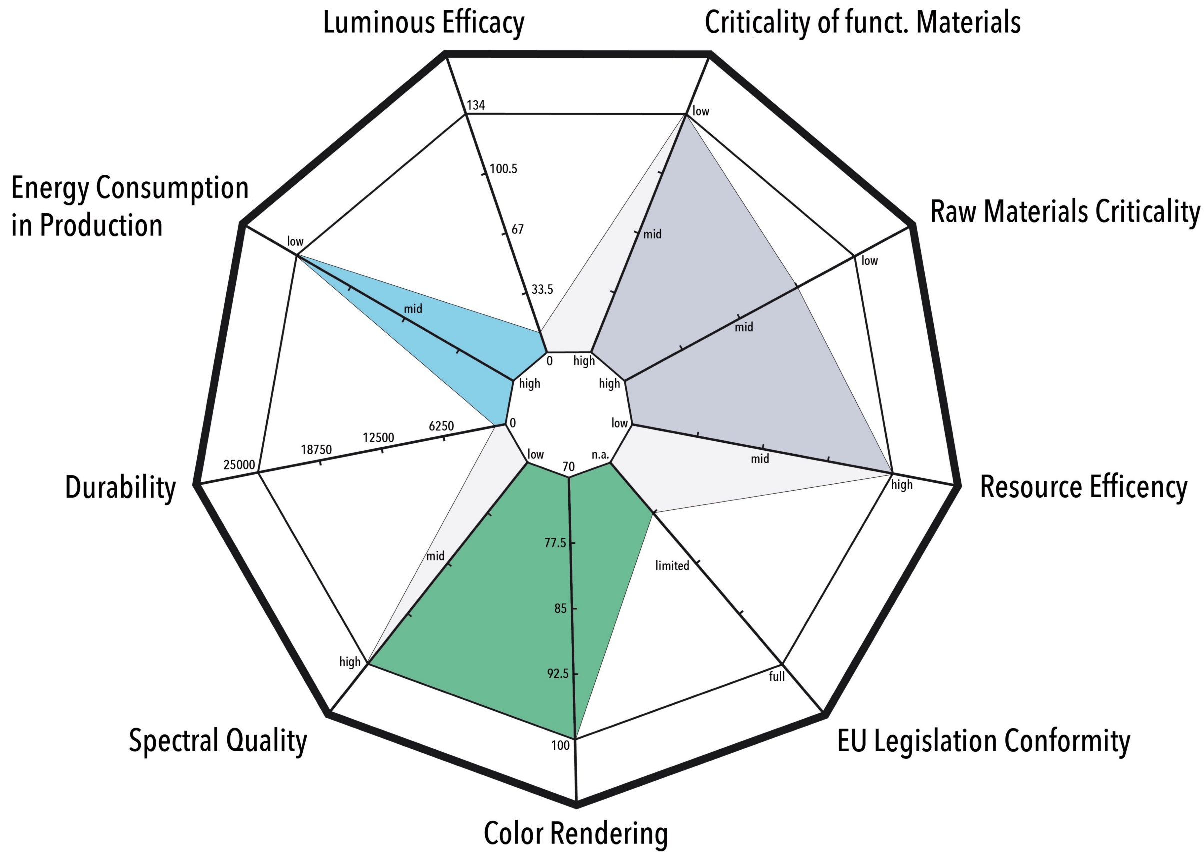


Fig. 32: Assessment results OSRAM standard incandescent bulb.

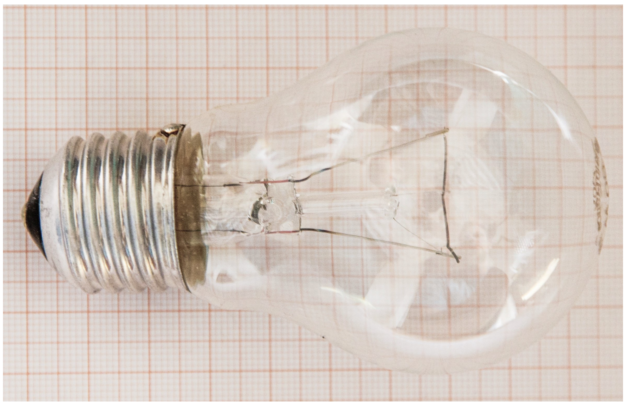


Fig. 33: OSRAM standard incandescent bulb.

12.1.2 Voltolux Halogen Spotlight 50 W 350 lm

With a *luminous efficacy* of 7 lm/W this lamp offers the worst performance in this evaluation. Compared to the best performing product (OSRAM Retrofit Classic A60: 134,3 lm/W) or the best performing LED spotlight (OSRAM LED Star 35 GU10: 88,5lm/W) the drawbacks in efficiency of this product become evident. With regard to *energy consumption in production* the only available source offering specific data about a halogen lamp is an LCA study conducted by OSRAM in 2009. Here the halogen lamp exhibits an increased cumulated energy demand (CED) in production compared to a standard incandescent lamp but features significantly lower values than a reference CFL and a reference retrofit LED at the time. However it should be noted that this value represents a halogen lamp in classic light bulb shape, which may deviate from that of a spotlight designed for GU10 sockets. Based on that and considering the layout of this lamp incorporating a coated reflector cup, filler gas and thick walled casing made of quartz it is assumed that this halogen spot light achieves a low to medium rating regarding energy consumption during production. *Durability* until complete failure (2000h) yields double the lifetime of a standard incandescent bulb but is low in comparison to values reached by CFL and LED lamps. Data on luminous efficacy and durability was retrieved from retail packaging.

With regard to *spectral quality* the halogen spotlight offers the emission characteristics of a thermal emitter, which includes a continuous spectrum similar to daylight encountered during evening hours. Having a build in UV-light filter this lamp reaches the highest rating possible. The spectral properties of this illuminant result in a color-rendering index of 100. Hence it achieves the highest possible rating in terms of *color rendering*. *EU legislation conformity* is currently satisfied. The product is in compliance with the directives REACH, RoHS and WEEE but it is assumed that a ban due to its low grade of efficiency is put into place in the near future. (European Union 2012b)

Concerning *resource efficiency,* the low overall material content of this luminaire and its simplistic design result in an efficient layout compared to CFLs and LEDs. Material losses during production are assumed to be low on grounds of mature processes in glass production and metals processing (OSRAM 2009; DOE 2012). Recycling is potentially feasible in large quantities with high rates of recovery. Provided that adequate waste treatment is in effect, the glass and metal contents of halogen spotlights can be recovered with comparatively low effort. Due to those circumstances the Voltolux Halogen was determined to be a resource efficient light source. As to *raw materials criticality* the only raw material used for the manufacturing of halogen lamps regarded as critical is tungsten. With regard to *criticality of functional materials,* this halogen spotlight does not comprise any functional materials according to the definition used in this work. Therefore it features, like a standard incandescent lamp, no criticality with respect to said substances. (European Commission 2014; Zepf et al. 2014)

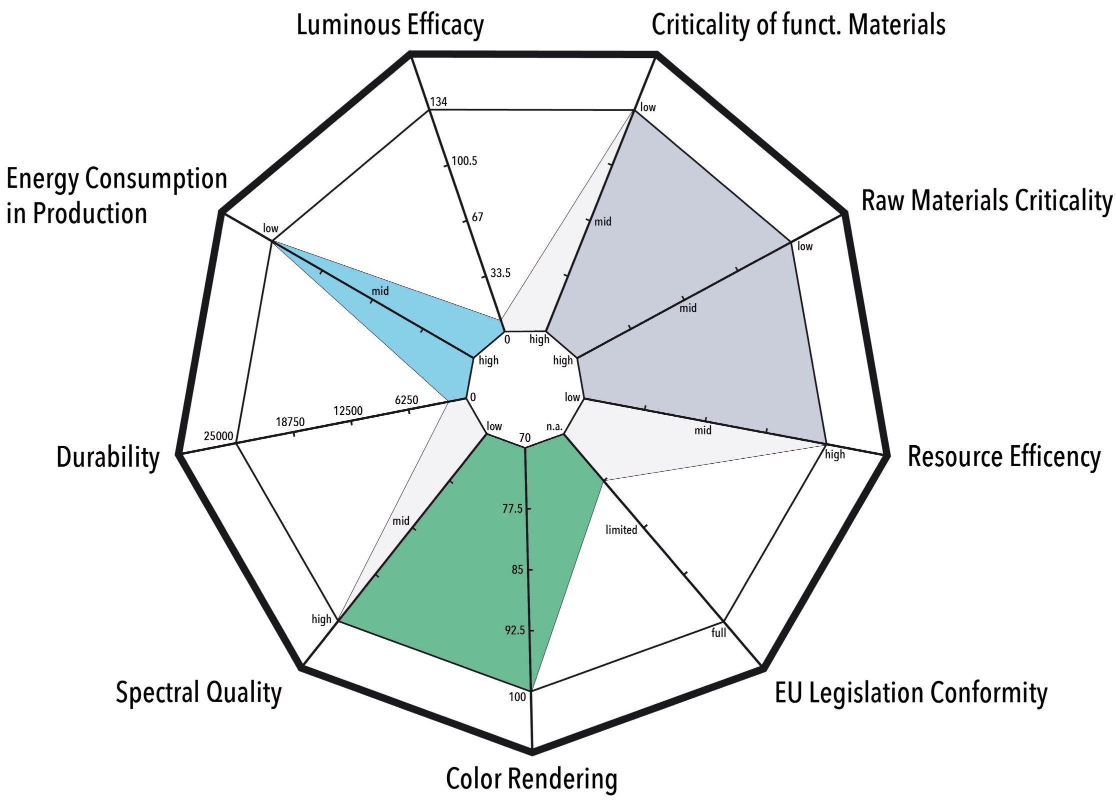


Fig. 34: Assessment results Voltolux Halogen Spotlight.

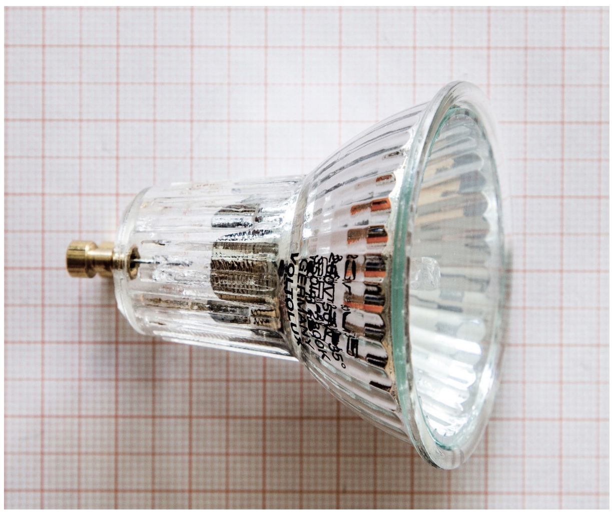


Fig. 35: Voltolux Halogen Spotlight.

12.1.3 OSRAM Dulux Superstar 14W

With a *luminous efficacy* of approximately 53lm/W the compact fluorescent lamp OSRAM Dulux Superstar 14W provides acceptable performance in the middle of the applied scale. It offers substantially higher performance than the standard incandescent lamp but falls considerably short in comparison to the best performing LED lamp in this evaluation. Considering *energy consumption in production* the CFLs performance is located between the standard incandescent bulb and the included LED lamps. Since the available sources of information used for this treatise do strongly differ in terms of quantitative determination of cumulated energy demand (CED) during production of the named lamps, it is nevertheless possible to put the given values into relation. Both available studies consulted for this work determine the CED for a CFL to be of medium quantity compared to the high demands of LED bulbs and the low requirements of incandescent lamps respectively. In terms of *durability*, the lamp offers an average lifetime of 10000 hours before failure. This value results in a placement in the middle of the evaluation scale. It is ten times higher than the lifetime achieved by a standard incandescent lamp but less than half of the durability featured by the best performing LED lamps considered in the assessment of domestic light sources. (OSRAM 2009; DOE 2012; OSRAM 2017d)

With respect to *spectral properties* the OSRAM Dulux Superstar delivers a band spectrum of poor resemblance to that of a thermal emitter. It is dominated by three rather sharp peaks in the red, green and blue portion of the visible spectrum, which are divided by areas of low intensity or emission gaps in the blue and green region. Regarding *light quality* the lamp exhibits an indicated CRI value of 80, which is acceptable for domestic use but falls considerably short of the value achieved by an incandescent lamp. As far as *EU legislation conformity* is concerned, this CFL is currently not subject to any legal restrictions in terms of REACH, RoHS or energy efficiency regulations. Anyway it should be noted that mercury content in CFLs is in compliance to those regulations on the basis of an exception. Future legislation might induce a potential phase out of this technology in favor of non-hazardous, more efficient LED lighting. (OSRAM 2017d; European Union 2003; 2006; 2009a; 2012c)

With regard to *resource efficiency* it is assumed that the OSRAM Dulux Superstar features a high to medium performance in comparison to incandescent- and LED lamps. Added device-complexity due to extensive phosphor coatings and integrated electronic ballasts make for a higher number of involved manufacturing steps as well as increased overall materials input. Raised energy demands and production losses in the course of manufacturing are a result of those aspects. Recycling processes are impeded by challenging disassembly, health hazards due to mercury content and contamination of phosphors by mercury or other substances. As to *raw materials criticality*, the content of multiple rare earth elements in phosphors and tungsten as electrode material contribute to an increased degree of criticality. This statement is based on the fact that all publications used as source of information for this thesis rate rare earth elements as critical raw materials. In comparison to the standard incandescent lamp the OSRAM Dulux Superstar does not show an increased *criticality of functional materials.* Apart from the consistent rating of rare earth elements as raw materials with high criticality in respective literature, no available evidence was found during the research for this work, which indicated potential problems regarding supply of light converting materials themselves. (Virey 2015, DERA 2016)

Other materials than phosphors incorporated in the CFL do not conform to the definition of functional materials used for this treatise. Substances of content such as glass, plastics and metals are part of large scale industrial processes which are non-specific for the lighting industry. (LED professional 2016a; European Commission 2014; Zepf et al. 2014; OSRAM 2008)

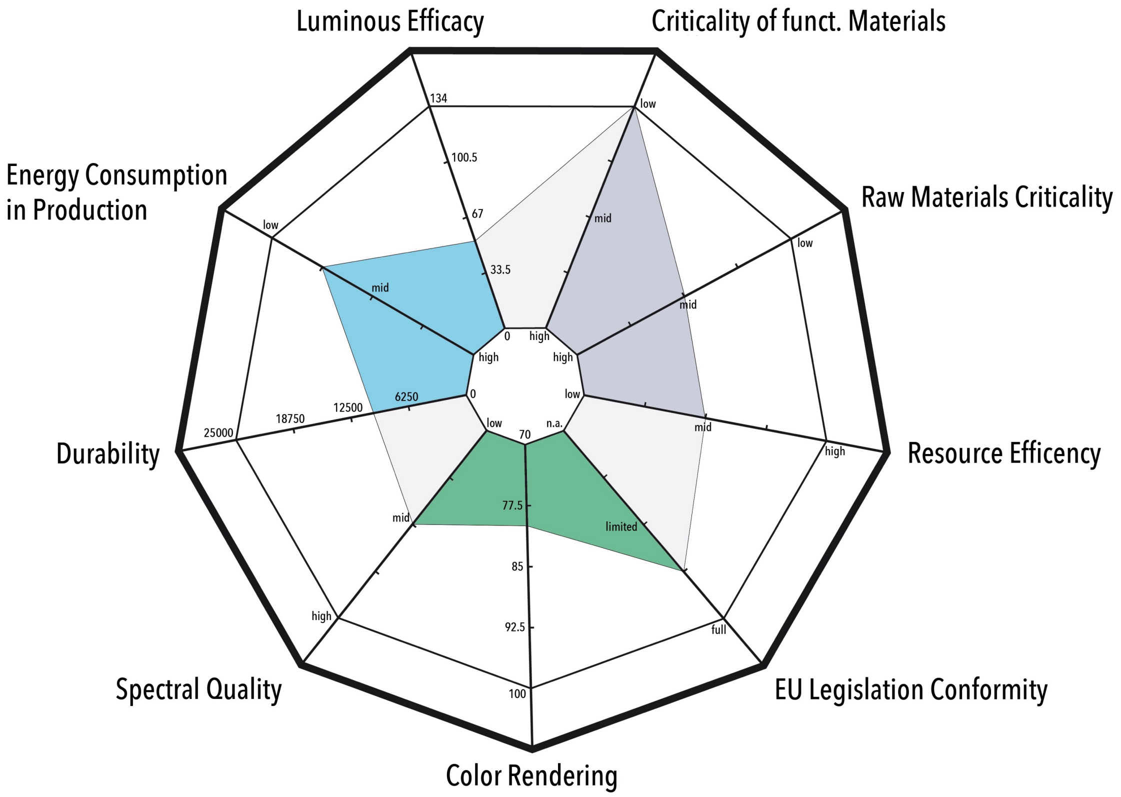


Fig. 36: Assessment results OSRAM Dulux Superstar 14W.

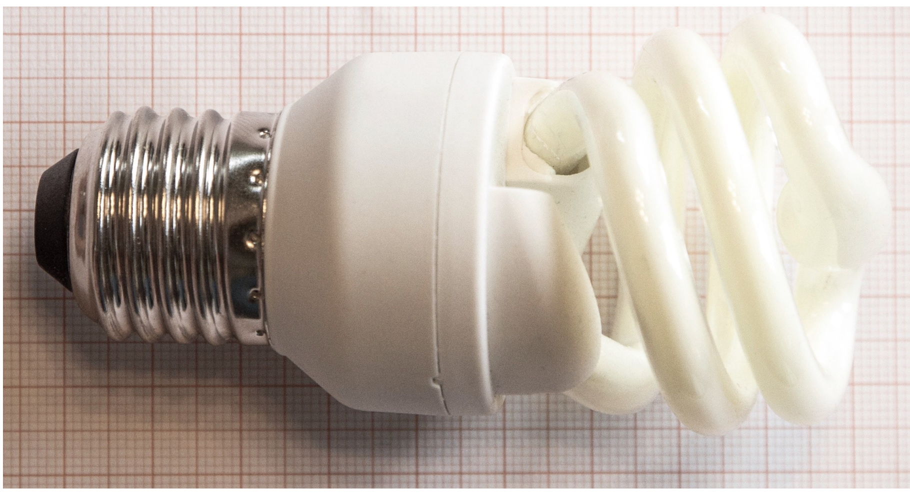


Fig. 37: OSRAM Dulux Supertstar 14W.

12.1.4 OSRAM LED Retrofit Classic A60 (LED Filament)

Featuring a specified *efficacy* of about 134lm/W this lamp is the best performing device included in the assessment of domestic light sources. It surpasses a standard incandescent lamp by the factor of ten and offers double the light yield in comparison to a conventional compact fluorescent lamp. With regard to *energy consumption in production* the information given by the sources used for assessment are in agreement that LED lamps hold the highest demand for primary energy in production. It has to be acknowledged that those studies are not fully representative since LED lighting has made considerable progress after their date of publication (the latest study was published in 2012). Projections made in one study (DOE) however assume considerable reductions in energy demand by the year 2016. After consideration of those outlooks the primary energy demand for LED bulbs was determined to be high in comparison to incandescent lamps and CFLs nonetheless. In terms of *durability* this lamp offers medium to high durability with 15000 hours of operation. It is important to note that this specified period of time does not denote the average period until complete failure. It describes the average phase of use after which light output drops below 70% of the initial value. This period of time considerably surpasses the use phase of the standard incandescent lamp and also exceeds the durability of conventional CFLs. (OSRAM 2009; DOE 2012; OSRAM 2017e)

As to *spectral quality* the emission spectrum of the OSRAM Retrofit Classic bulb does not fully resemble the characteristics of the thermally emitting incandescent lamp. Its continuous spectrum shows deficits in the green and red portion of the visible spectrum but holds clear advantages over the incomplete spectrum most fluorescent lamps exhibit (Baer et al. 2016). Regarding *color rendering*, this LED filament bulb offers acceptable color rendering for residential purposes with a CRI of equal or superior to 80. In this respect, the lamp falls short in comparison to an incandescent lamp but features a performance comparable to the CFL chosen for evaluation (OSRAM Dulux). In terms of *EU legislation conformity* it is the best performing light source considered. It holds conformity to all applicable law and is not expected to be non-compliant to future legislation. (European Union 2003, 2006, 2012b-c; LEDVANCE 2017)

As to *resource efficiency* the OSRAM Retrofit bulb features a medium to low performance in comparison to the standard incandescent bulb and the compact fluorescent lamp. Its production incorporates energy-intensive and lossy processes such as substrate growth and epitaxy (DOE 2012; Khanna 2014). The layout of this LED filament bulb features an elevated number of small LED dies covered in a comparably large encapsulation of phosphor material. On the other hand the technical layout of this lamp does not require any heat sink structures. Moreover disassembly of the lamp led to the assumption that the bulb-like casing and structures for filament support are modified components of incandescent light bulbs. By using modified versions of already existing glass structures and fabrication tools significant reductions in materials usage can be achieved compared to dedicated metal bodies. Glass structures and exposed position of the modular LED filaments facilitate disassembly for recycling. However the electrical driver unit of this lamp is encapsulated within the base causing for difficult retrieval. With respect to *raw materials criticality* LED lamps provide the worst performers of this assessment. All consulted publications rate multiple raw materials necessary for the production of LED lighting devices to be critical. Rare earth elements used in phosphor materials as well as indium and gallium, which are required for the manufacturing of LED dies are unanimously considered to be critical. In terms of *criticality of functional materials* in LED lamps, research for this work indicates that functional materials for the production of LED luminaires such as phosphors, wafers for epitaxy and LED dies are currently available without restrictions. According to publicly available summaries of market reports issued by industry affiliated market researchers, all of those materials are currently subject to production ramp up, over-capacity or strongly competitive price policies. Despite the comparably high demand for specialized functional materials and strong influence of ownership of intellectual property, the current situation appears to show no signs of increased criticality. Nevertheless it has to be noted, that information about the supply situation within the solid state lighting industry is difficult to obtain. Access to comprehensive market reports issued by expert market researchers requires fees that lie beyond academic budget. (European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015; LED professional 2016a; Wise Guy Report 2017)

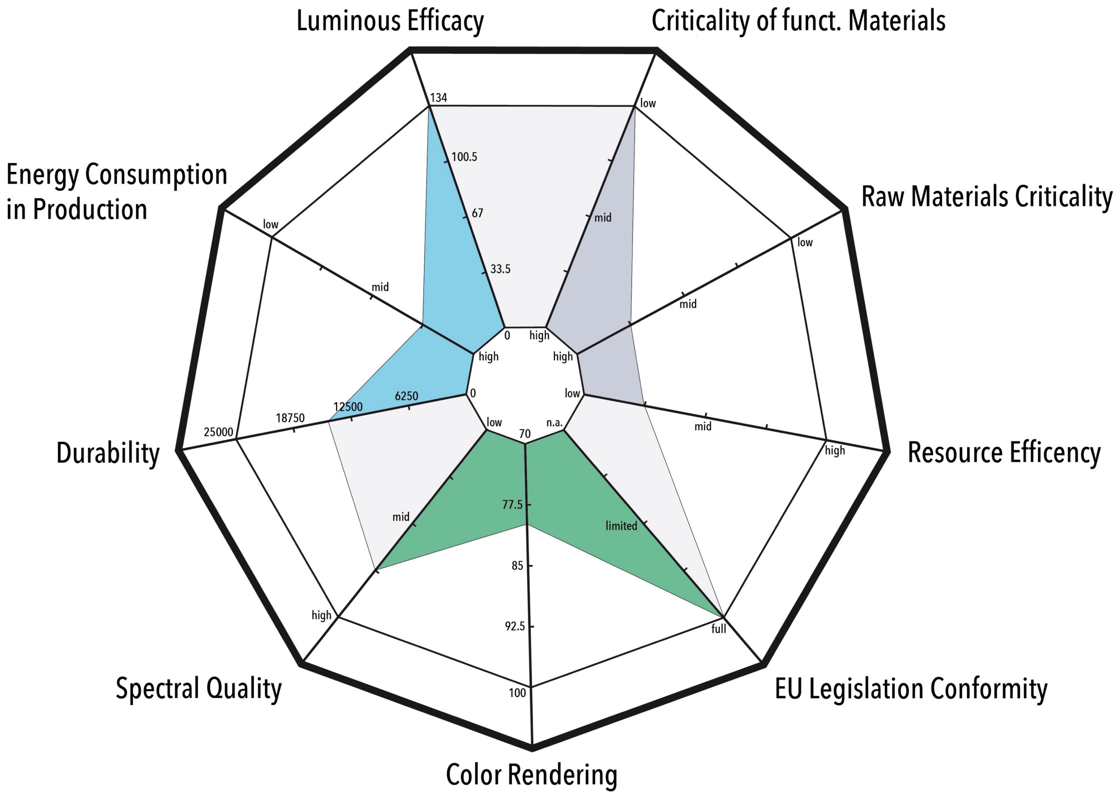


Fig. 38: Assessment results OSRAM LED Retrofit Classic A60.

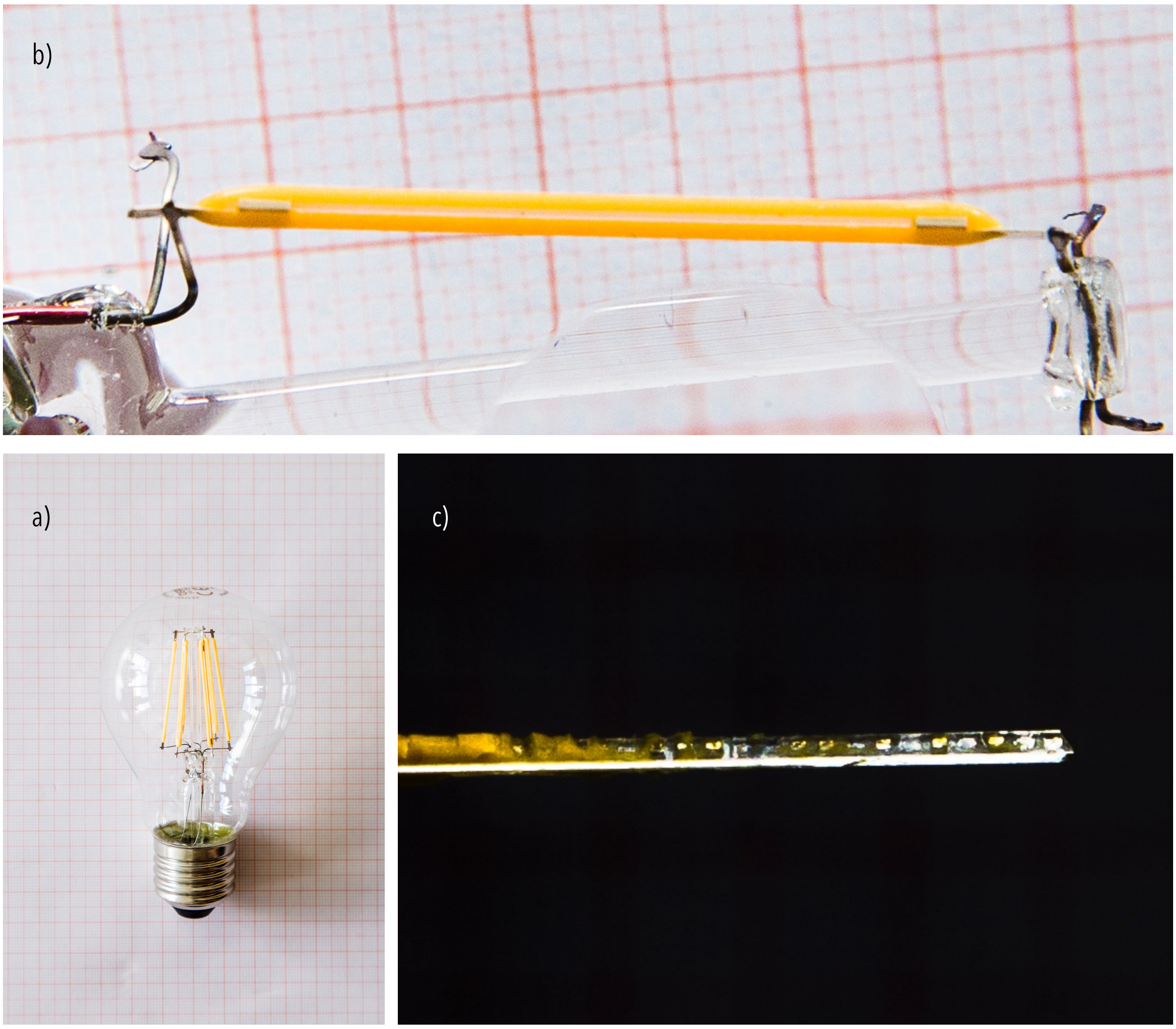


Fig. 39: OSRAM Retrofit Classic A60.

a) Product before disassembly.

b) Close-up view of a single LED filament

c) Close-up view of a removed LED filament after the partial removal of the phosphor coating. Single LED chips are visible on the exposed glass carrier.

12.1.5 OSRAM LED Star Classic A60 (frosted bulb)

With an *efficacy* of 100lm/W this lamp is among the systems, which achieve high performances regarding efficient transformation of electrical current to visible light. With respect to *energy consumption in production* this product is assumed to necessitate high quantities of energy. The disassembly of this product revealed a large heat sink body made from aluminum beneath an external plastic coating. Furthermore 17 surface mounted LED chips on an aluminum carrier plate thermally connected to the internal aluminum body by heat conductive paste were discovered. According to the findings of a study conducted by the DOE (2012) regarding the life-cycle assessment of LED lighting products, elevated contents of aluminum and the incorporation of numerous individually phosphor coated LED dies contribute to high expenses of energy during production. *Durability* of this lamp is specified with 15000 hours of use until significant reduction in light output is expected to occur. (OSRAM 2017b)

In terms of *spectral quality* the OSRAM LED Star offers a continuous spectrum with deficits in the blue to turquoise (around 480nm) and deep red (over 620nm) regions compared to a standard incandescent lamp. Apart from those shortcomings, the spectral distribution is in resemblance to an incandescent lamp. With a specified color-rendering index of 80, this product delivers acceptable values for the use in domestic lighting applications. In terms of *EU legislation conformity* this lamp is not subject to any present or expected legal restrictions. (Messer 2015a; OSRAM 2017b; European Union 2003, 2006, 2012b-c)

Regarding *resource efficiency* several aspects cause for the determination of the performance to be low. The layout of this product incorporates a large two-piece aluminum casing as heat sink as well as an increased number of individual surface mounted LED-chips what results in raised materials usage in comparison to other LED lamps and conventional light sources. On grounds of added overall chip surface for each individual device it is also assumed that production losses during die manufacturing are heightened. In terms of recyclability the device features a rather modular setup where the circuit board carrying the surface mounted LED chips can easily be removed from its aluminum carrier plate. Also the driver unit is held by a plug socket, which facilitates removal for dedicated electronics-recycling. However the aluminum body is tightly covered by an outer casing made of white plastics impeding quick separation. Considering *raw materials criticality* the OSRAM LED Star requires materials, which are currently regarded as critical in relevant publications. The content of indium and gallium in blue emitting LED dies and the rare earth content in applied phosphor layers result in a medium to high criticality rating. The fact that the quantities of those materials required for the annual production of luminaires lies distinctively below the overall annual production of those raw materials is assumed to have a mitigating effect. In terms of *criticality of functional materials* the research conducted for this work gave no indication to assume increased criticality of functional materials such as phosphors, substrates or LED dies. (European Commission 2014; Zepf et al. 2014; DERA 2016, pp. 88-91)

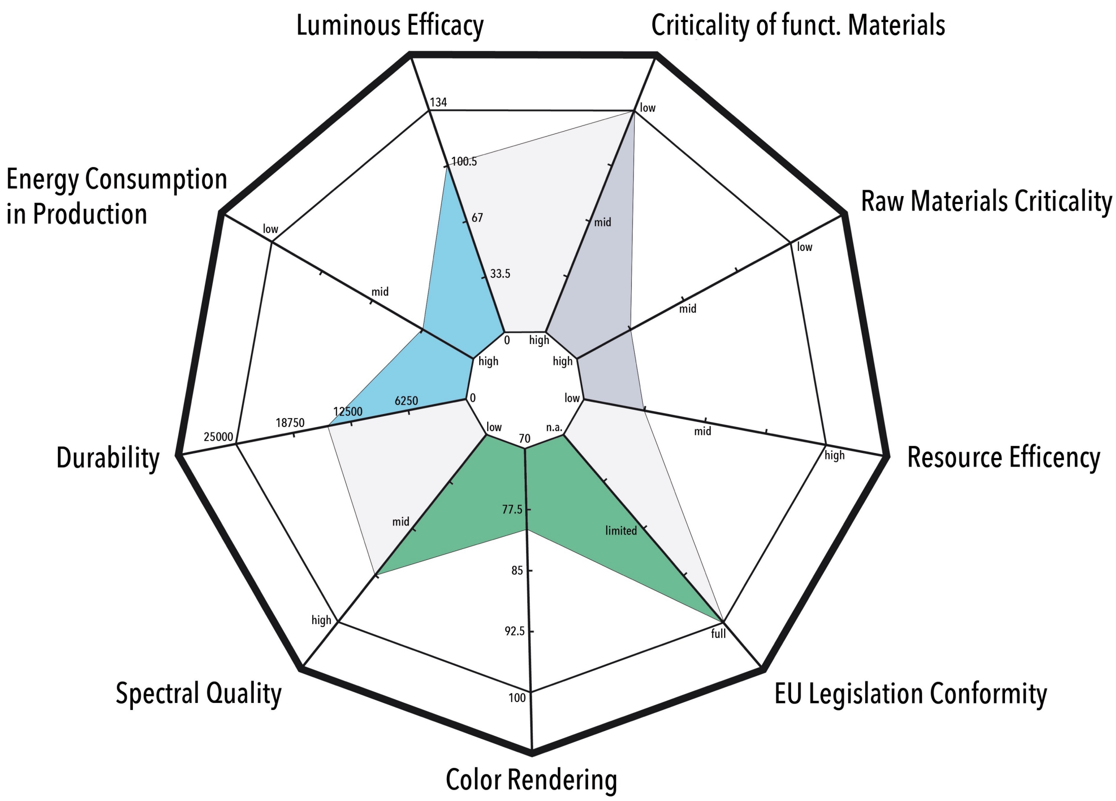


Fig. 40: Assessment results OSRAM LED Star Classic A60.

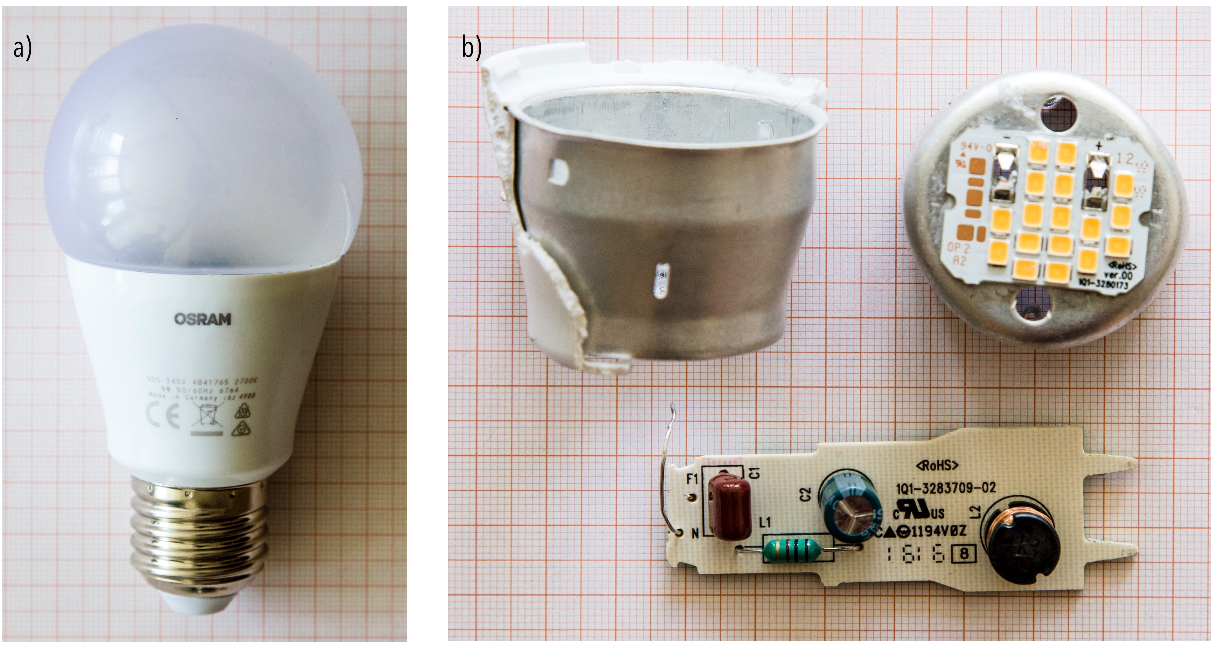


Fig. 41: OSRAM LED Star Classic A60.

a) Product before disassembly.

b) Upper left: Plastic coated aluminum housing cup for increased heat dissipation. Upper right: Circuit board with SMD-chips thermally connected to an aluminum carrier plate. Lower middle: Electrical driver unit with functional components.

12.1.6 Xavax High Line LED 9.2W (frosted bulb)

This lamp achieves a *luminous efficacy* of 87.6lm/W, which constitutes a medium performance in comparison to the best performing illuminant in this assessment. With regard to *energy consumption in production* lamp is among the worst performers. A casing made from aluminum and the incorporation of an elevated number of phosphor coated surface-mount LED chips accounts for presumably high energy demands in the production of this illuminant. It offers high *durability* of 25.000 hours of continuous operation until significant reduction in light output occurs. (Xavax 2017; DOE 2012)

Spectral Quality of this lamp lies above the values achieved by the other products for domestic lighting and is only surpassed by incandescent lamps. The spectral distribution is continuous and exhibits only a small peak in the blue region while also providing relatively strong emission in the deep red part of the visible spectrum. Despite its close resemblance to the emission spectrum of an incandescent lamp it still shows system inherent deficits . Also with regard to *color rendering* (CRI 90) this lamp reaches the best performance among the considered lamps that do not use the principle of thermal emission. Furthermore full compliance to *EU legislation* is granted. (Messer 2015a; Xavax 2017; European Union 2003, 2006, 2012b-c)

This illuminant performs poorly with regard to *resource efficiency*. Its technical layout is similar to the OSRAM LED Star Classic described before. However it incorporates more surface-mount LED chips with lower luminous output resulting in additional materials usage of semiconductor materials and phosphor. Therefore losses during production are assumed to be increased in comparison to the aforementioned lamp. Disassembly was hampered by a strong adhesive bond between the lamp casing and the opaque plastic cup enclosing the chip carrier. Easy removal of this circuit board enabled for quick extraction of functional components such as electric driver unit and SMD LED packages. The aluminum body is tightly covered by an outer casing made of white plastics impeding quick separation. Considering *raw materials criticality* the Xavax High Line requires materials, which are currently regarded as critical in relevant publications. Contents of indium and gallium in blue emitting LED dies and the rare earth based phosphor layers result in a medium to high criticality rating. Regarding *criticality of functional materials* the research conducted for this work gave no indication to assume increased criticality of functional materials such as phosphors, substrates or LED dies. (European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015; LED professional 2016a)

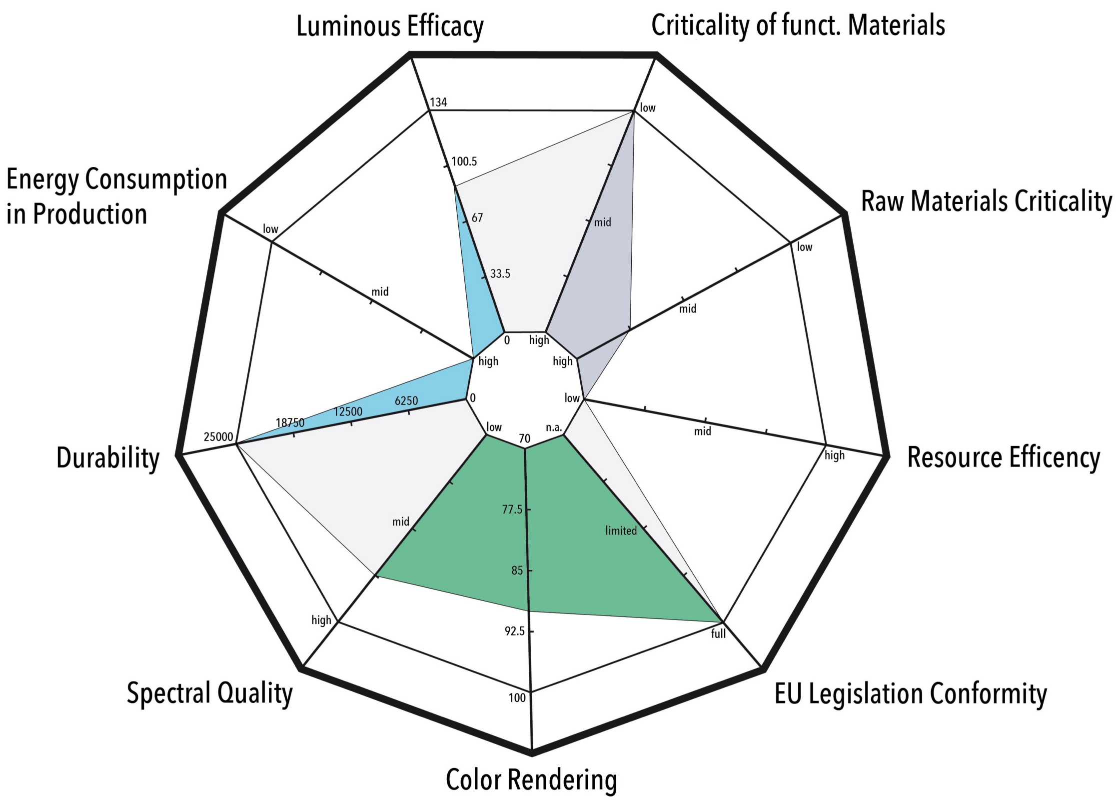


Fig. 42: Assessment results Xavax High Line.

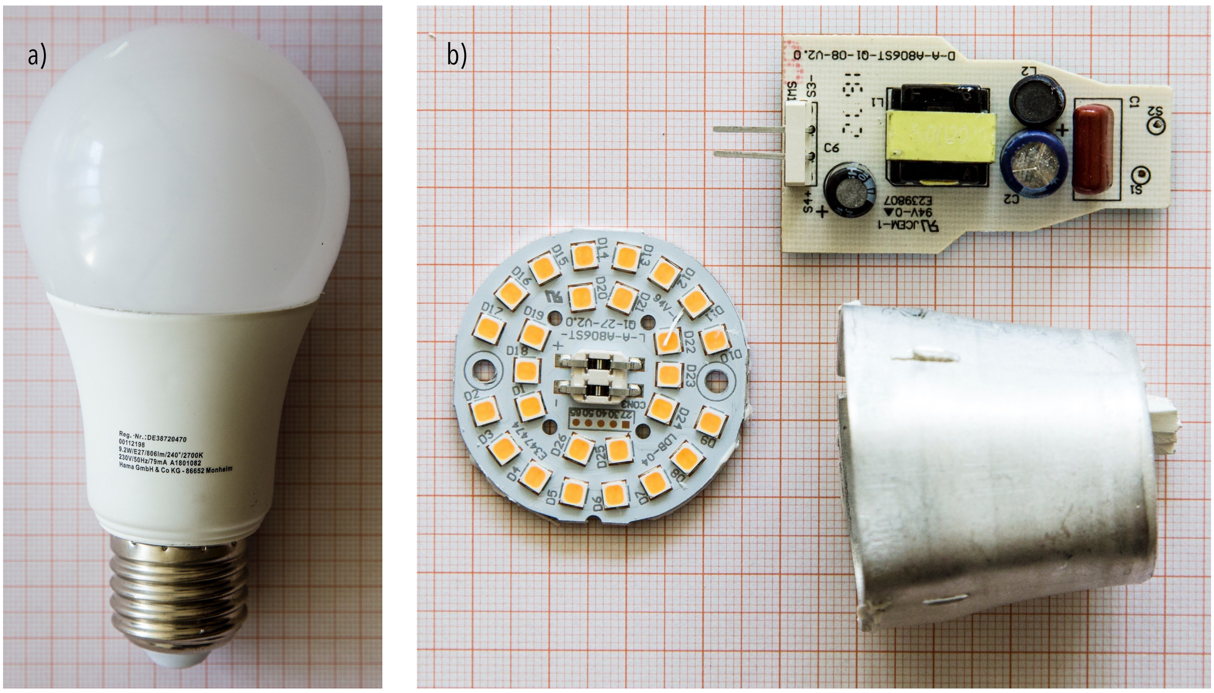


Fig. 43: Xavax High Line. a) Product before disassembly. b) Left: Printed circuit board with surface mounted low-output LED chips. Upper right: Electrical driver unit with functional components. Lower right: Aluminum housing cup after removal of the plastic coating.

12.1.7 VOLTOLUX LED Spotlight 5 W 390 lm

Offering a *luminous efficacy* of 78lm/W this spotlight designed to replace halogen spotlights in GU10 sockets consumes less than a tenth of electrical power compared to a halogen spotlight with similar luminous flux offered by the same brand. In terms of *energy consumption during production* the evaluation is based on assumptions. This course of action is based on the circumstance that the studies used as basis of information do not contain data about the specific environmental impacts of LED spotlights. However with regard to basic functional principles the components of bulb shaped lamps and spotlights show no fundamental discrepancies. Based on the findings of the DOE (2012) and OSRAM (2009), it is assumed that LED luminaires feature a significantly higher demand for primary energy in production than conventional light sources. According to the detailed information given in the study conducted by the DOE on the formation of cumulative energy demand (CED) during production, this lamp is assumed to be among the worst performers of all domestic light sources considered. This life cycle assessment carried out by the United States Department of Energy on the ecologic impacts of LED lighting identifies aluminum heat sinks to greatly contribute to the CED in production. Also the fabrication of LED packages is described as an energy-intense process which significantly contributes to overall energy demand in manufacturing. As this device incorporates 30 single LED dies all covered with individual phosphor layers (30 packages) and a solid aluminum body for increased heat dissipation, the assumption that this device requires comparably high quantities of energy during production is further confirmed. With regard to *durability,* the Voltolux spotlight is among the top performing luminaires. It offers 25000 hours of operation until the light flux drops below 70% of the initial value. (BAUHAUS 2017)

Considering *spectral quality* no data about spectral properties could be retrieved during the research for this work. However in view of the technological working principles of this lamp and available manufacturer specifications, this lamp is assumed to feature blue-emitting LED dies in combination with one type of yellow broadband phosphor. The resulting continuous spectrum with deficits in the regions of green and deep red provides light with state of the technology characteristics. *Spectral quality* is therefore rated as medium to high. In terms of *color rendering* the lamp offers acceptable performance with a CRI of equal or superior to 80. *EU legislation conformity* is completely fulfilled. The lamp is rated energy class A+ and no upcoming legal restrictions are expected. (BAUHAUS 2017; Baer et al. 2016, pp. 262-278; European Union 2003, 2006, 2012b-c)

As to *resource efficiency* the assessed Voltolux device represents the worst performing system. The employment of a solid aluminum casing (finned heatsink) and the combination of 30 low performance SMD chips including phosphor, lead frame and bonding wires result in an increased usage of material. Those layout characteristics add to the already comparably high demand for resources and energy in production. Furthermore the incorporation of 30 single LED packages is assumed to entail increased production losses in the course of LED package production compared to systems which use fewer more powerful chips. Recyclability is impeded by the fact that this device requires an increased number of work steps in order to be taken apart. The removal of the glass cover and underlying aluminum carrier plate carrying the SMD LED packages necessitates careful manual work to be non-destructive. On the other hand this lamp features a through hole technology electric driver unit which can be taken apart for reuse of the components with comparably low effort (in contrary to the cast in unit of the OSRAM filament bulb for instance). Like all LED based lighting devices in this evaluation, this lamp also depends on raw materials which are rated as critical. Therefore the use of materials such as indium, gallium and rare earth elements result in a medium to high *criticality of raw materials.* Regarding *criticality of functional materials* the research for this work gave no indication of current or impending supply shortages. Hence it was rated to be low. (European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012,2015; LED professional 2016a)

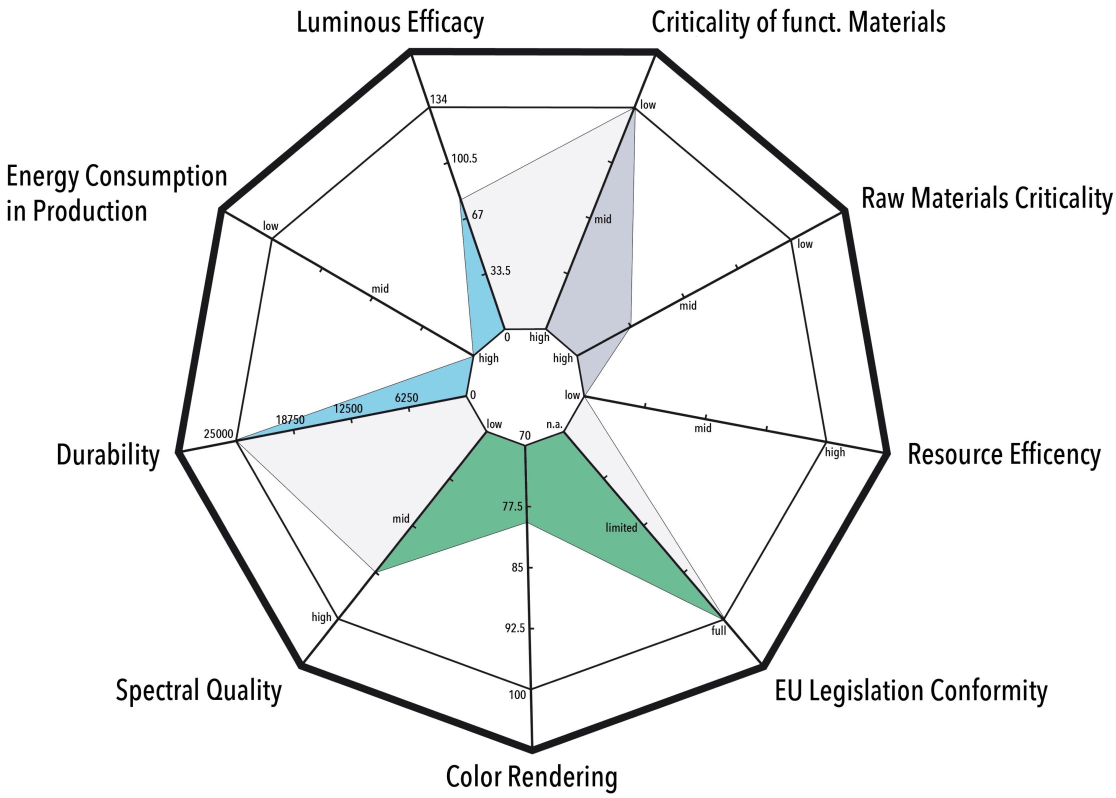


Fig. 44: Assessment results Voltolux LED Spotlight

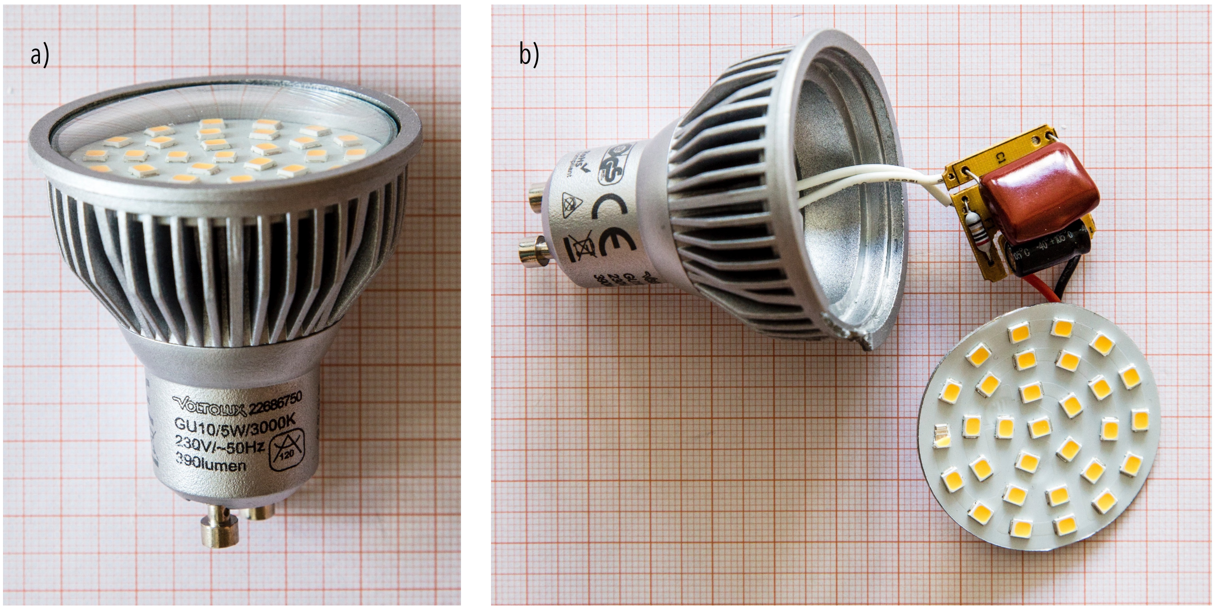


Fig. 45: Volotlux LED Spotlight. a) Product before disassembly. b) Left: Aluminum heat sink/housing. Upper right: Electrical driver unit presumably soldered by hand. Lower right: Aluminum carrier plate with low-output SMD packages.

12.1.8 OSRAM LED Star 50 GU10

With a specified *efficacy* of 81,4lm/W this LED spotlight provides medium performance in relation to the best performing systems included. Compared to the other LED luminaires regarded it features average luminous efficacy. Nevertheless it surpasses the performance of a halogen spotlight, which requires 50 W instead of 4,3 W to reach the same light output, by far. Considering *energy consumption in production*, no specific data for LED spotlights could be obtained during the research for this work. Nonetheless it is assumed that this lamp necessitates comparably low amounts of energy to be produced in comparison to other LED lighting devices considered. The reasons for this assumption are based on the following circumstances. During disassembly it became evident that no heat sink structures are part of the design and that all comprised LED dies are integrated within a single phosphor coated package. The circuit board, which also carries the electric driver on its underside is connected to the glass body by a thin aluminum carrier ring. The greatly reduced aluminum content in comparison to other LED devices and the reduced phosphor quantities necessary for the employed one-package-approach lead to a decrease in content of energy-intense structures (DOE 2012). Moreover the product features a reflector coated dichroic glass body. This component is normally found on halogen spotlights. Therefore it is assumed that the energy expense for the production of the casing is very similar to the comparably low quantity necessary for the body of the aforementioned luminaire (OSRAM 2009). Regarding *durability* the OSRAM LED Star spotlight provides on average acceptable 15000 hours of operation until significant reduction in light output occurs. (DOE 2012; OSRAM 2009; OSRAM 2017c)

In terms of *spectral quality* this lamp achieves a medium to high rating. It was not possible to obtain detailed information about the spectral properties of this specific product. Hence the rating was conducted based on the assumption that the emission spectrum of this lamp resembles the characteristics found on other products (of same specified CRI) of the brand (compare OSRAM Classic A60 and LED Star Classic A60). With a specified color rendering index of 80 the spotlight provides acceptable *light quality* in the mid-range of the evaluation scale. In respect of *EU legislation conformity* this lamp achieves a high rating due to conformity to all relevant regulations. Furthermore no infringements are expected in the near future. (European Union 2003, 2006, 2012b-c; OSRAM 2017c)

As to *resource efficiency* the product exhibits some advantages in terms of layout, production and recycling in comparison to other systems currently available. A more efficient use of functional materials is the result of packaging. By incorporating eight single LED chips into one phosphor coated package directly mounted on the surface of a circuit board, a reduction in overall quantity of light converting material is achieved. Moreover the same circuit board also carries the electric driver unit on its backside. Also the number of chips necessary to reach a light output of 350lm brings advantages regarding materials usage as well as decreased overall production losses during the process of chip manufacturing. Due to the comparably simple layout, which is a combination of a glass body and a single circuit board carrying all functional units recycling is also facilitated. The lamp proved to be easy to disassemble by taking the glass body, the LED-package and the circuit board apart by using a conventional screwdriver. This modular layout is assumed to favor reuse of the respective components after dedicated collection. *Raw materials criticality* is heightened according to the studies used as basis of information for this work. Contents such as indium and gallium required for the manufacturing of LED-dies as well as rare earth elements are rated to be critical. In relation to incandescent lamps, which rely on tungsten as single moderately critical raw material, raw materials criticality was determined to be medium to high. With regard to *criticality of functional materials* research for this treatise found no evidence for increased criticality or supply shortages of materials such as substrates, epitaxial wafers or phosphor materials. Sources of information rather indicated a current surplus of manufacturing capacities as new production facilities are coming into existence. (European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012,2015; LED professional 2016a)

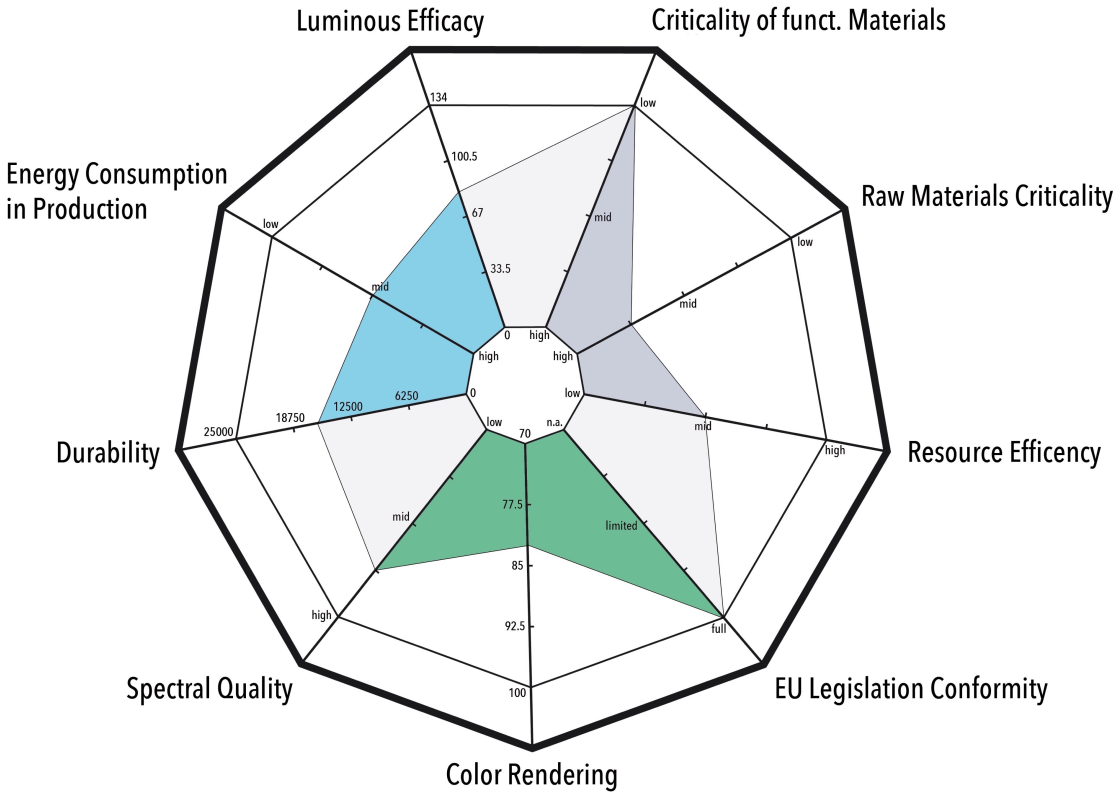


Fig. 46: Assessment results OSRAM LED Star 50

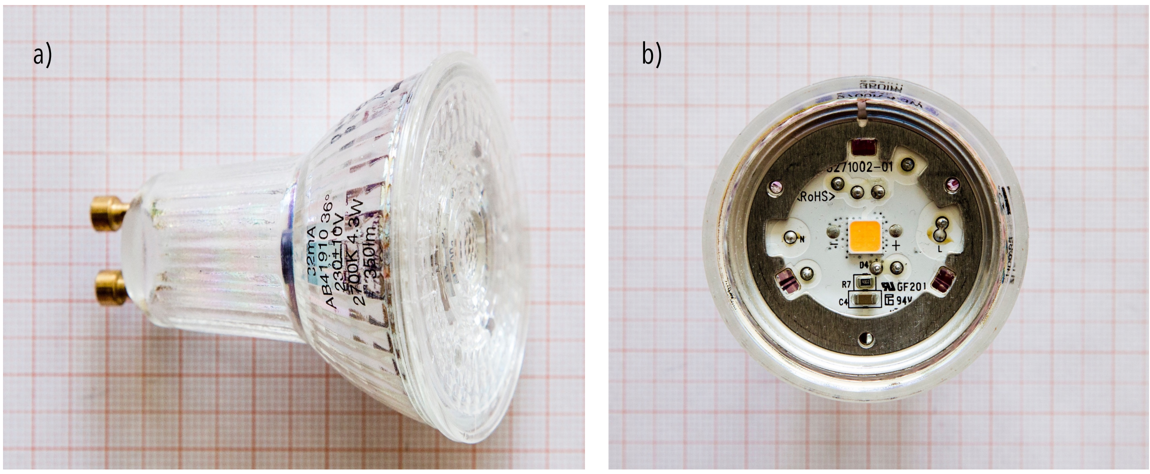


Fig. 47: OSRAM LED Star 50. a) Product before disassembly. b) Top view of the lamp after removal of the clear plastic diffusion lens. Visible are the aluminum retainer ring and the top side of the integrated circuit board with a single phosphor coated package of eight single LED dies. Not visible: Underside of the circuit board with functional components of the electrical driver unit.

12.1.9 Philips Hue White Color and Ambiance

This tunable smart light features a range of *luminous efficacy* depending on desired emission color and color-correlated temperature. This range extends from 38 lm/W at a CCT of 2000K over 57lm/W at 3000K to approx. 90 lm/W at a CCT of 4000 K for the emission of white light. None of the publications used as basis of information includes a life cycle assessment or determination of cumulative energy demand for the production of LED systems utilizing red-green-blue color mixing. Because of that, the rating of *energy consumption in production* is based on estimates considering the layout of this lamp. Multiple chips of different emission color, comparably complex electronic structures needed for emission control and wireless communication as well as a housing made of aluminum for better heat dissipation are assumed to be important factors in terms of raised energy consumption in production. Compared to non-adjustable, single-emission LED-systems the Philips Hue is therefore assumed to require high amounts of energy during production. In terms of *durability* the system is among the best performers with an average specified lifetime of 25000 hours before significant reduction in lumen output occurs. (DOE 2012; OSRAM 2009; Philips 2017d)

Regarding *spectral quality* the lamp exhibits a continuous spectrum with a deficit in the portion of the visible spectrum lying between blue and green at about 480 to 490nm (turquoise). Depending on the chosen color correlated temperature, this gap takes more or less influence on the overall spectral properties. At a chosen CCT of 2700K the spectral distribution is, apart from a strong peak in the red part of the visible spectrum, in resemblance to that of an incandescent lamp. At a CCT of about 4100K however the emission spectrum is characterized by two strong peaks in the regions of blue and red (the latter being overlapped by a broad peak in the green to yellow region). Especially in this configuration the resemblance to the spectral properties of a thermal emitter is reduced. As a result *spectral quality* was determined to exhibit a range spanning from mid to good. Regarding *color rendering* the color correlated index can reach values of up to 96.8 at a CCT of 2700K whereas this value drops to 82.7 for a CCT of about 4100K. Compared to a standard incandescent lamp the light quality of the Philips Hue bulb is determined to range from medium to good. As to *EU legislation conformity* the considered device stands in full agreement to regulations such as WEEE, RoHS and REACH. Despite the fact that no EU energy rating is available for this product, it currently fulfills the requirements in terms of energy efficiency issued by the European Union. Moreover no disagreement to future legislation is expected. (Messer 2015b; European Union 2003, 2006, 2012b-c; Philips 2017d)

Regarding *resource efficiency* the product was rated with regard to layout, production and recycling. Compared to other solid-state lighting devices featuring a single chip design, the incorporation of multiple LED dies of different color, conductive paths and complex control electronics necessitate an increased usage of material. Also the use of an aluminum casing for the purposes of enhanced heat dissipation causes increased expenses of material. The manufacturing of LED chips of different chromaticities is assumed to result in comparably high production losses in the course of wafer preparation, epitaxial growth and chip fabrication. Recyclability of this product is hampered by the high grade of integration within the device. Manual disassembly showed the need for multiple tools and diligent work in order to take the functional components of the device apart. With regard to *raw materials criticality* the Philips Hue bulb features a medium degree of criticality. The built in LED dies contain the metals indium and gallium which are considered to be critical by relevant literature. However criticality is reduced in comparison to phosphor converted systems by the fact that no rare earth elements, which are also rated critical by those publications are utilized. In terms of *criticality of functional materials* the situation is also eased by this circumstance. The lack of phosphor materials lessens the list of incorporated functional materials to substrates and epitaxial wafers needed for the production of LED dies of the respective colors. Alike the other LED illuminants included in this evaluation, research gave no indication of problems concerning the supply of those materials. Reports on price decline and overcapacity suggest a low degree of criticality. (DOE 2012; European Commission 2014; Zepf et al. 2014; Herf 2012; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015; LED professional 2016a)

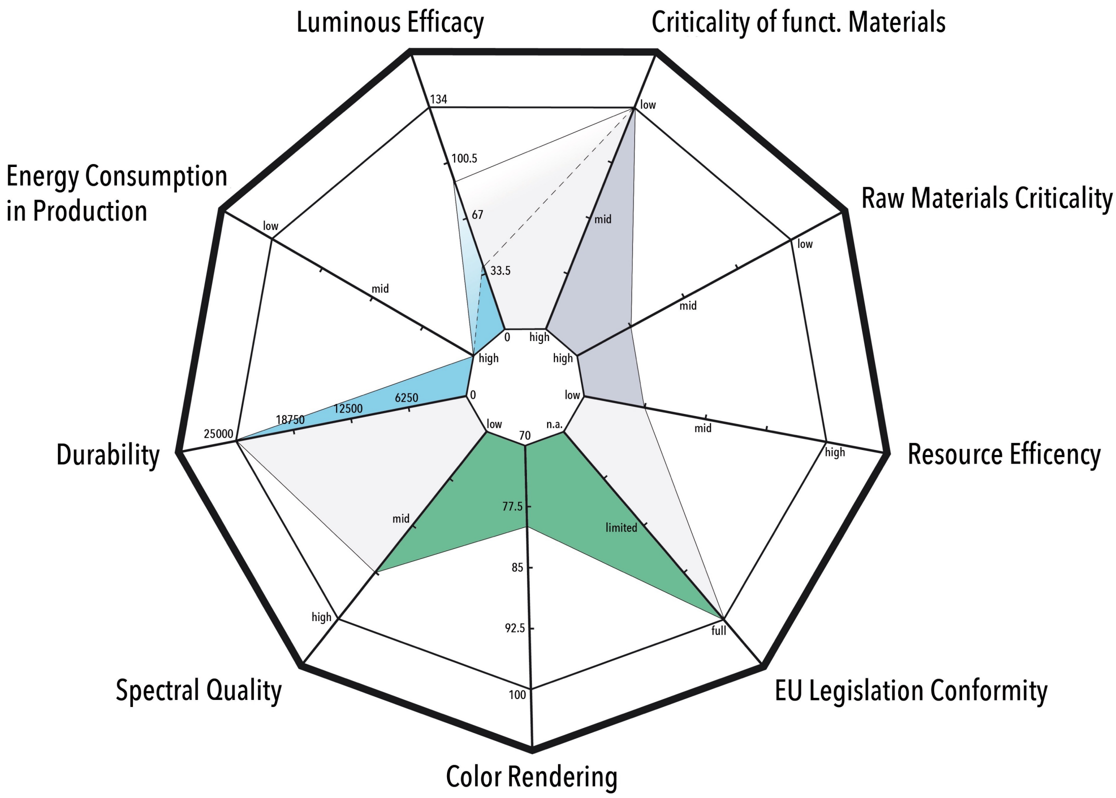


Fig. 48: Assessment results Philips Hue White Color and Ambience.

12.2 Industrial/Commercial Lighting

The following section contains the results of the evaluation of light sources which are intended for illumination in the industrial and commercial sector. A selection was made with regard to the most relevant systems of traditional lighting systems in and their LED counterparts. Included are one particularly efficient and long lasting fluorescent tube in order to demonstrate what performances can be achieved by this technology and a standard fluorescent tube offering enhanced color rendering capacities. In comparison to that, two LED tube lights designed to replace fluorescent tubes in their respective lamp fixtures are considered. One features peak performance showcasing the current potential of solid-state lighting on a mass production scale. The other representing the average performance of competitively priced LED tube lights manufactured by a market leading company at the moment.

LED tube lights as well as fluorescent tubes are available in a variety of length, light output and color correlated temperature. Moreover it is important to discern between two types of ballast. Fluorescent tubes are either operated with conventional ballasts or electronic ballasts. Due to their working principles electronic ballasts allow for increased efficiency in comparison to conventional types. Those ballasts represent the more up-to-date solution. However to provide comparability among the chosen LED tubes and fluorescent lamps devices using a conventional electromagnetic ballast (fluorescent) or ballast substitutes in the form of jumpers (LED) were picked for assessment. This approach takes account for the fact that both types of lamps can be operated by the same fixture. This way a more meaningful comparison can be made due to the absence of any pre-installed ballasts, which take influence on performance and materials consumption. Moreover the lamps were selected to feature a uniform length of 1200mm, cool white color correlated temperatures of about 4000K and similar values in terms of light output. (Baer et al. 2016, pp. 213ff.)

The following table shows the specifications and order of appearance of the products included in the assessment of light sources for industrial/commercial application.

Table 6: Considered light sources for industrial/commercial lighting

	Philips Master TL-D Eco	Philips Master TL-D De Luxe	Philips CorePro LEDtube 16W840 C G	OSRAM Substitube Advanced ST8A-EM 14W/840 1200mm
Design	Fluorescent Tube	Fluorescent Tube	LED Tube T8	LED Tube T8
Wattage Equivalent	n.a.	n.a.	n.a.	n.a.
Wattage	32 W	36 W	16 W	14 W
Output	2650 lm	2800 lm	1600 lm	2100 lm
Efficacy	82 lm/W	77,8 lm/W	100 lm/W	150 lm/W
CCT	4000 K	4000 K	4000 K	4000 K
CRI	85	91	80	80
Durability [h]	12000 h	12000 h	30000 h	50000 h
Cycles	n.a.	n.a.	200000	200000
Temperature Range	n.a.	n.a.	–20° to 45°	–20° to 50°
Socket	G13	G13	G13	G13
Beam Angle	n.a.	n.a.	240°	150°
Energy Class	A	A	A+	A++
Price	4,82 €	4,62 €	11,08 €	21,82 €
Origin	Netherlands	Netherlands	China	China

12.2.1 Philips Master TL-D Eco

This luminaire features an *efficacy* of 82 lm/W, which represents the highest value of the fluorescent lamps considered in this evaluation. It has to be noted that values of around 80 lm/W reflect the state of technology for this type of lamp and can be found on a variety of respective products. Regarding *energy consumption in production* no data specifically describing the energy expenses necessary for the production of fluorescent tubes was available. Hence the determination of the relative value is based on assumptions. The fact, that a fluorescent tube shares its basic technical layout with a compact fluorescent lamp provides the basis for further estimates: Fluorescent tubes (1200mm length) exhibit a larger phosphor covered glass body than conventional CFLs but in turn lack internal ballasts (ballasts are usually located within the lamp holder). Apart from electrodes fused in the glass body of the lamp and external connector pins, no additional contents of metal are included. In contrast to an LED tube which features a more complex design consisting of a substantially higher number of single components such as a multitude of single SMD-LED packages, integrated electrical driver unit and heat sink structures made from aluminum the fluorescent tube is assumed to require lower amounts of energy in production. In terms of *durability* this lamp offers an average failure rate of ten percent after 12000 hours of use. This value lies below the average normally achieved by this class of products and is considerably lower than the lifetimes achieved by LED tubes made by leading manufacturers. (OSRAM 2009; DOE 2012; Philips 2017c)

With respect to *spectral quality* the spectrum of this lamp exhibits band-like discontinuous characteristics with deficits in the green, yellow and far-red portions of the visible spectrum. Dominating narrow peaks of red, green and blue emission color further discern the output of this lamp from the spectral distribution of daylight. With a color-rendering index of 85, the Philips Master TL-D Eco delivers adequate *color rendering* for industrial applications and workspaces. *EU legislation conformity* is currently granted due to an exception made for the enforcement of to the RoHS directive. On grounds of its mercury content, this luminaire does not comply with this regulation and may be subject to a ban if the current special approval is revoked in medium term. (Philips 2017c; European Union 2003, 2006, 2009b, 2012c; Haitz and Tsao 2010)

As to *resource efficiency* this illuminant shows a layout, which is comprised of a linear glass tube and metallic elements forming electrodes, electrical contacts and end caps. Compared to an LED tube light the number of functional components is significantly lower. In the face of this low grade of complexity in comparison to an LED tube this product is regarded as a highly resource efficient solution. Also the losses in production are assumed to be low in relation to its LED counterparts. Continuous operation of the glass smelter for glass tube production and mature large-scale industrial processes in metal production are assumed to result in low production losses. The phosphor coating process of the glass tube is assumed to be an efficient process as well. Regarding recycling, contamination by mercury content and fractions of evaporated metal impedes the reuse of phosphor coatings. The main portions of glass and metal can however be easily recovered by specialized industrial processes. On the basis of those circumstances, resource efficiency of this fluorescent lamp is considered to be high in comparison to the LED tube lights included in this work. Rare earth content of light converting materials in fluorescent tubes contributes to an increased *raw materials criticality* for this illuminant. Also incorporated tungsten in electrodes is classified as critical raw material. This rating is a result of the fact that all publications consulted in the making of this work determine rare earth elements and tungsten to be critical substances. As to *criticality of functional materials,* no indication was found during the research for this work, that supply of phosphor materials itself is deemed to suffer from potentially restricting influences. Other materials than phosphors incorporated do not conform to the definition of functional materials used for this treatise. Substances of content such as glass and conventional metals are part of large-scale industrial processes, which are non-specific for the lighting industry. (Baer et al. 2016, pp. 200-206; Virey 2012, 2015; DOE 2012; LED professional 2016a; DERA 2016, pp. 88-91; European Commission 2014; Zepf et al. 2014)

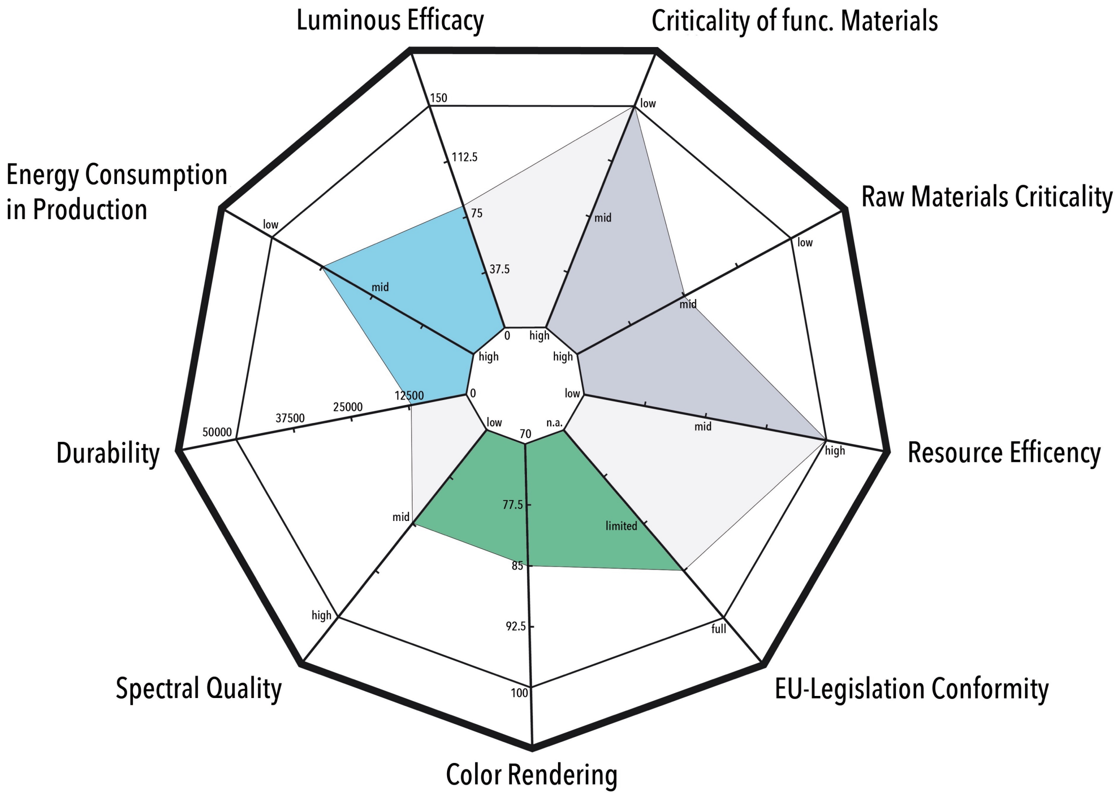


Fig. 49: Assessment results Philips Master TL-D Eco.

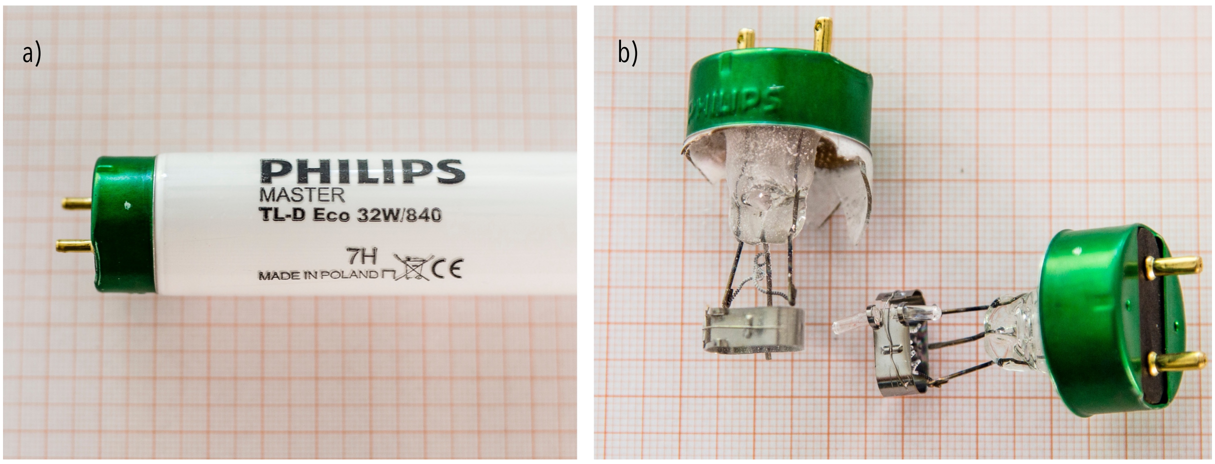


Fig. 50: Philips Master TL-D Eco

a) Product before disassembly

b) End-caps with electrodes

12.2.2 Philips Master TL-D De Luxe

This fluorescent tube features an *efficacy* of 78 lm/W, which lies slightly below the average value for quality products in this dimension. This can be explained by the improved color-rendering index of this lamp. It is assumed that augmented spectral properties necessitate the use of additional phosphor materials resulting in increased conversion losses by Stokes Shift. Regarding e*nergy consumption in production* the same aspects described in the previous evaluation of the Philips Master TL-D Eco are assumed to apply. Both lamps feature the same technical layout with the distinction of an enhanced color-rendering index, which can be allocated to a modified phosphor composition. The implications of said modifications for the CED in production could not be determined. In terms of durability, this luminaire offers specified 12000 hours of operation until an average failure rate of ten percent is reached. (OSRAM 2009; DOE 2012; Philips 2017b)

Regarding *spectral quality* the Philips TL-D De Luxe shows enhanced emission properties in the blue to green region of the visible spectrum in order to achieve an improved color-rendering index. The discontinuous emission spectrum is dominated by three narrow peaks in the red, green and blue portion of the visible spectrum with gaps in the yellow and green regions. Those characteristics are in poor resemblance to those of thermal emitters. Due to its enhanced spectral properties, this lamp features a comparably high *color-rendering index* of 91. *EU legislation conformity* is currently granted on the basis of an exception regarding the RoHS directive. Falling prices and increased adoption of solid-state lighting systems may however lead to a mid-term phase out of mercury containing fluorescent tubes. (Philips 2017b; European Union 2003, 2006, 2009b, 2012c; Haitz and Tsao 2010)

Considering *resource efficiency* the same aspects as for the previously described Philips Master TL-D Eco were determined to apply. The rare earth content of the phosphors incorporated in fluorescent tubes and the tungsten electrodes contribute to an increased *criticality of raw materials* with regard to this lamp. This conclusion is drawn in the light of consistent ratings of high criticality in all publications used as source of information for this work. On the other hand no indication for raised *criticality of functional materials* could be found. Apart from the consistent determination of rare earth elements to be critical raw materials in respective literature, no evidence for potential problems regarding supply of light converting materials themselves was found. Other materials than phosphors incorporated do not conform to the definition of functional materials used for this treatise. Substances of content such as glass and conventional metals are part of large scale industrial processes which are non-specific for the lighting industry. (Baer et al. 2016, pp. 200-206; Virey 2012, 2015; DOE 2012; LED professional 2016a; DERA 2016, pp. 88-91; European Commission 2014; Zepf et al. 2014)

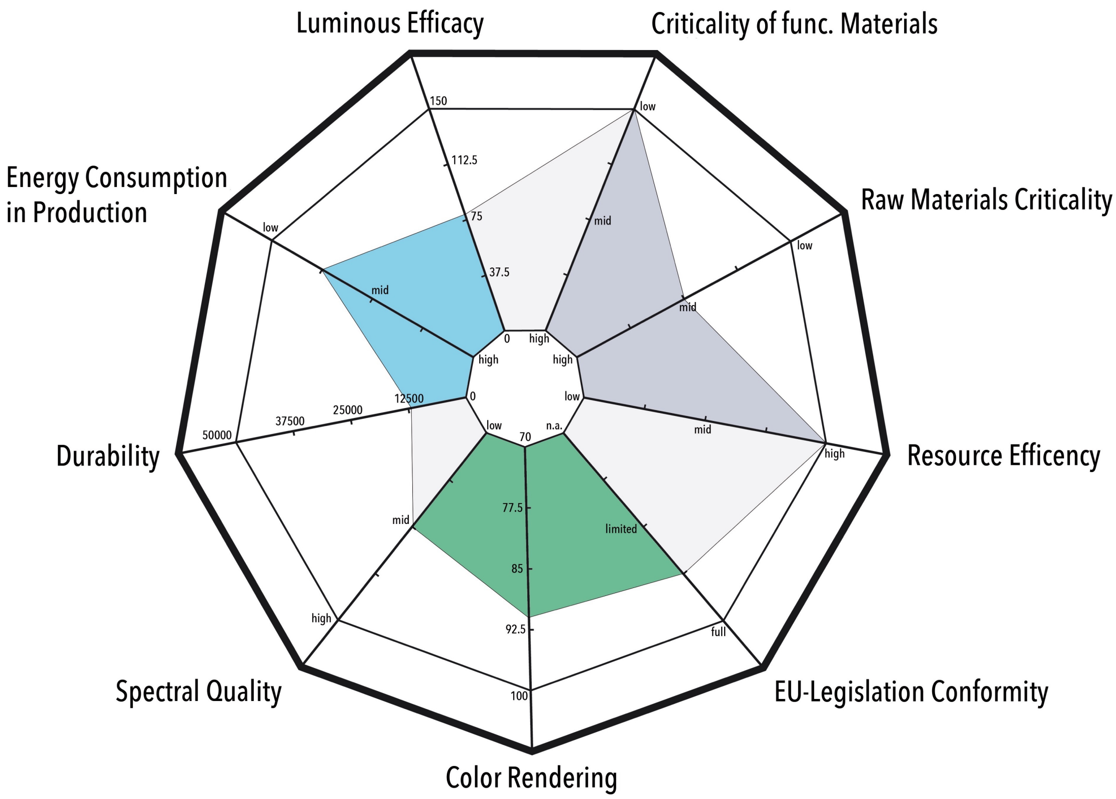


Fig. 51: Assessment results Philips Master TL-D De Luxe.

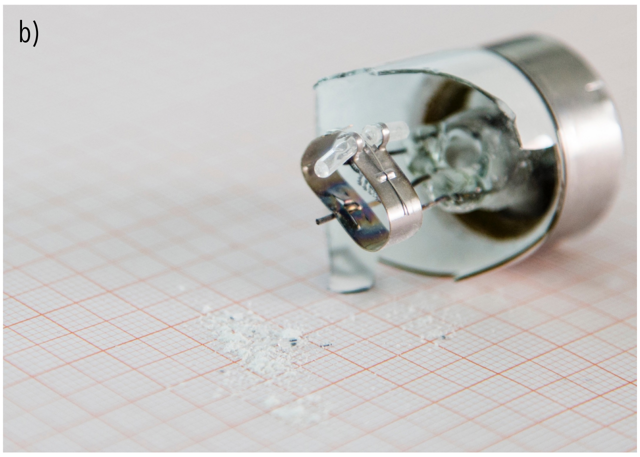


Fig. 52: Philips Master TL-D De Luxe

a) Product before disassembly

b) End-cap with electrode and phosphor powder residue

12.2.3 Philips CorePro LEDtube

This LED tube light features a *luminous efficacy* of 100 lm/W surpassing the fluorescent tubes included in this evaluation. With respect to *energy consumption in production* no data specifying the energy expenses involved in the production of this luminaire was available. Therefore a qualitative determination of energy demand in production was conducted based on estimates. Alike the fluorescent tubes included in this evaluation, the Philips CorePro exhibits a glass tube main structure with endcaps including metallic connector pins. The interior of the glass tube features a linear glued-in LED strip of single surface mounted LED chips. According to the high number of chips (72) it is assumed that energy intense processes involved in the production of phosphor coated single LED packages contribute to an increased CED compared to a fluorescent lamp. Also an integrated electrical driver unit is estimated to account for higher demands in energy compared to electrical leads and electrodes used in fluorescent lamps. *Durability* of this luminaire is specified with an average of 30000 hours until significant reduction of light output to a value of 70% of the initial value occurs. (DOE 2012; OSRAM 2009; Philips 2017a)

Regarding its *spectral quality*, the Philips CorePro LEDtube features a continuous spectrum with a strong emission peak in the blue range at approx. 450nm. An area of weak emission in the blue to green portion of the visible spectrum is followed by a broad peak in the yellow region ranging from green to red (500nm to 650nm). The far-red portion of the visible spectrum is comparably weak. The spectral properties of this device feature characteristics, which considerably surpass the band spectrum of the fluorescent tubes included in this evaluation in terms of resemblance to a thermal emitter. The color-rendering properties of this LED tube are specified with a color-rendering index of 80. This corresponds to the values achieved by standard fluorescent tubes in spite of the more complete emission spectrum of this LED illuminant. Regarding *EU legislation conformity*, this device is in full agreement to current regulations. Based on its contents and grade of efficiency no short- to mid-term restrictions are expected. (Philips 2017a; European Union 2003, 2006, 2012b-c)

With respect to *resource efficiency* this luminaire exhibits a technical layout dominated by 72 individual LEDs of comparably low output. Those SMD devices are linearly arranged on a narrow ribbon-like circuit board which is attached to the inside of the glass tube by an adhesive bond. This multitude of low-output chips is associated with a high input of functional materials. On the other hand corresponding low voltages of operation seem to result in thermal properties which do not require the use of heat sink structures usually made from aluminum. With regard to production losses elevated numbers of built-in LED dies are assumed to negatively affect resource efficiency in production. However production of the employed glass tubes is assumed to be subject to little losses due to mature large-scale manufacturing processes. As to recycling manual separation of the LED strip from the glass casing is hampered by a strong adhesive bond. Also the end caps, of which one contains the electrical driver unit, are strongly cemented to the glass tube hindering their extraction. Thermal treatment of end-of-life devices may be required for proper ungluing. In comparison to a standard incandescent tube, the *criticality of raw materials* was determined to be increased. All consulted publications on the subject rate the contained rare earth elements as well as the contents of indium and gallium as critical. *Criticality of functional materials* is determined to be low due to the fact that the research carried out for this work led to no evidence that any shortages in supply of those materials currently prevail. According to market reports phosphor materials, substrates and LED chips are currently available in sufficient quantities and production ramp ups regarding those materials are to be expected. (DOE 2012; European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012,2015; LED professional 2016a)

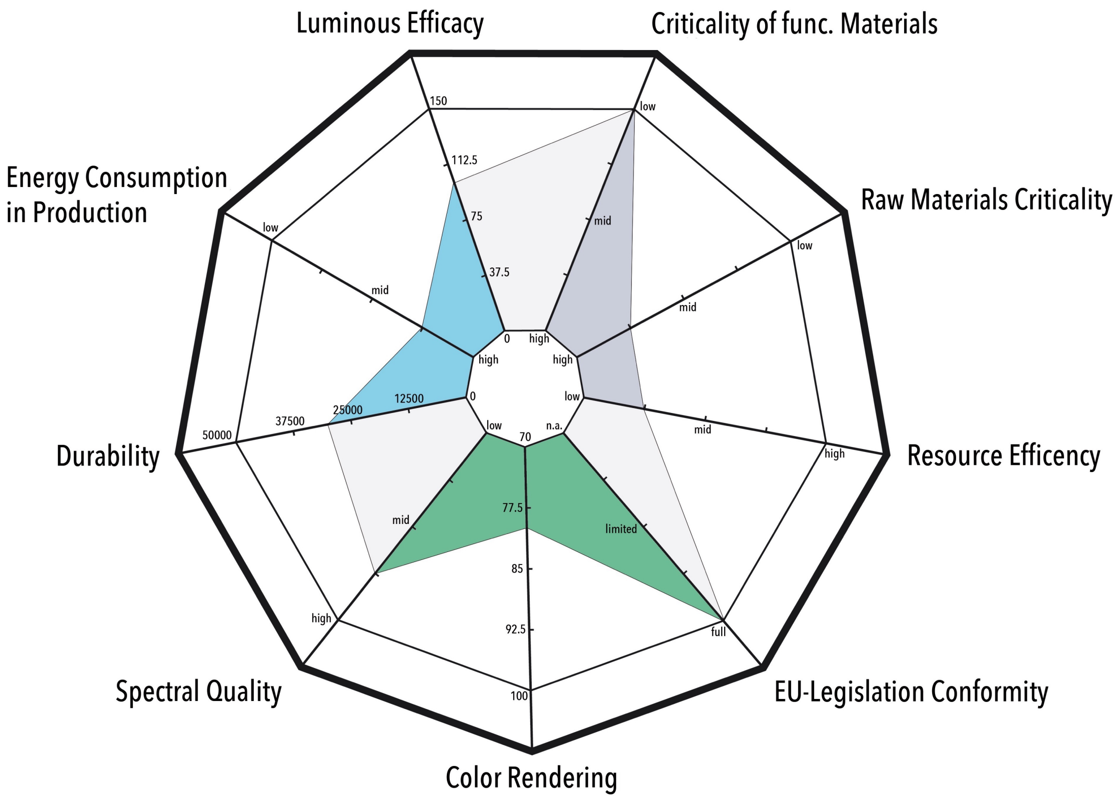


Fig. 53: Assessment results Philips CorePro LEDtube.

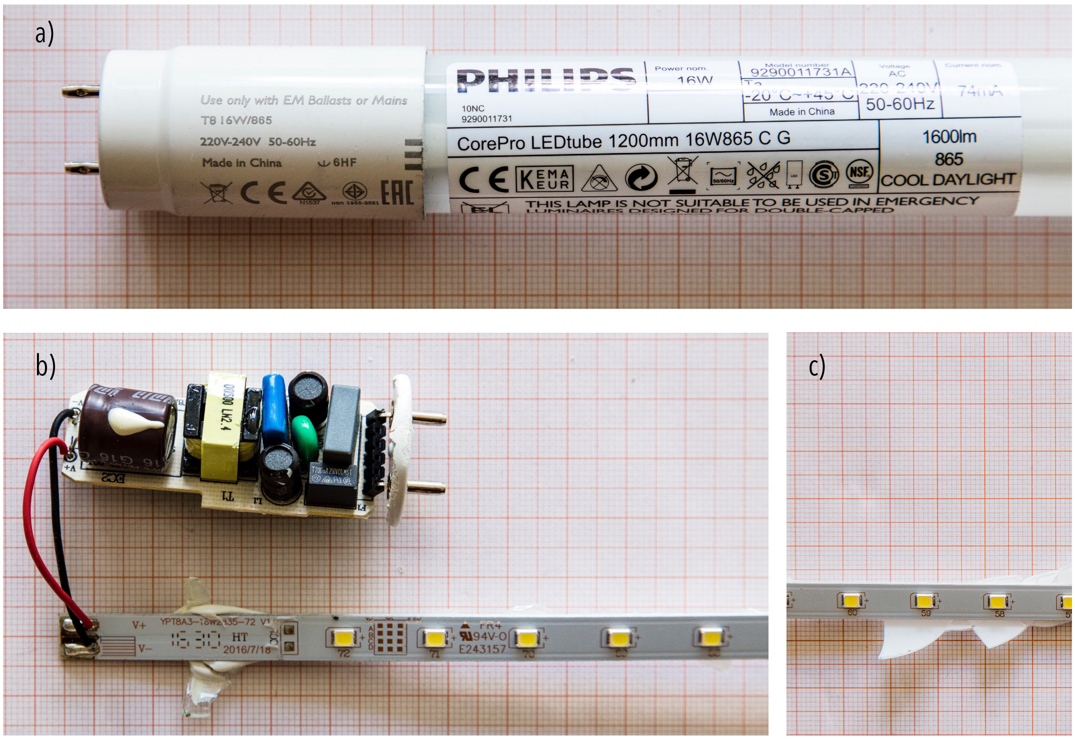


Fig. 54: Philips CorePro LEDtube.

a) Product before disassembly.

b) Upper left: Lamp socket containing the electrical driver unit after removal of its casing.

Middle: LED strip after destructive removal of the tubular glass housing with individual low-output SMD packages.

c) Remaining glass shards due to strong adhesive bond between LED strip and glass tube.

12.2.4 OSRAM Substitube Advanced ST8-A EM 14W/840 1200mm

Featuring an *efficacy* of 150 lm/W this solid-state lighting illuminant is the best performing device among the light sources for industrial purposes in this assessment. It substantially outperforms both the included fluorescent tubes and the mid-range LED tube chosen for comparison. Regarding *energy consumption in production* this luminaire allows for savings due to the use of a polycarbonate tube instead of coated glass. However the incorporation of 81 surface mounted LED packages is considered to be an energy intense solution. Specified with a *durability* of an average of 50000 hours of operation until significant reduction in light output occurs it also represents the best performing system featured in this work. Compared to the fluorescent tubes included, which show a rate of total failure of ten percent after 12000 hours of operation, this value proves to be superior. (OSRAM 2009; DOE 2012; OSRAM 2016;)

Regarding *spectral quality* no data could be obtained. The manufacturer of this lighting device did not provide any photometric data of this lamp at the time this evaluation was conducted. Also no other sources of information could be retrieved due to lack of data. However on grounds of basic technical layout and state of the technology the emission spectrum of this illuminant is assumed to resemble the characteristics of the Philips CorePro LEDtube previously described. According to that the device exhibits a continuous spectrum with a sharp peak in the blue portion and a broad peak around the yellow region of the visible spectrum. Deficits are expected to show in the turquoise region at about 480nm and the far-red part at wavelengths greater than 650nm. Compared to the band spectrum of fluorescent lamps, which mainly exhibit gaps between three sharp peaks in the red, green and blue portion the spectral properties of this LED illuminant is in better resemblance to a thermal emitter. With respect to *color rendering* the manufacturer specifies a color-rendering index of 80. This value correlates to performances achieved by standard fluorescent tubes and provides sufficient light quality for industrial appliances. As to *EU legislation compliance* this device is in full agreement to current regulations. Based on its contents and grade of efficiency no short- to mid-term restrictions are expected. (OSRAM 2016; European Union 2003, 2006, 2012b-c)

Regarding *resource efficiency* the layout of this luminaire exhibits the disadvantage of a large number of SMD packages. The use of a high number of low output chips is assumed to have beneficial effects on the durability but necessitates a high input of functional materials for the production of individual devices. Also losses during production are estimated to be elevated compared to fluorescent lamps by reason of a large quantity of integrated LED dies. The luminaire offers a structure that enables quick and easy dismantling for recycling. Functional and structural components can be taken apart without tools. SMD packages are arranged in an exposed position on a strip-like circuit board what enables quick non-destructive removal. The tubular polycarbonate casing can be easily and non-destructively retrieved for mono-fraction recycling or reuse. Due to content of materials, which are determined to be critical by the publications providing the basis of information for this work, this device is rated to be subject to elevated *raw materials criticality*. In comparison to the included fluorescent tubes additional contents of gallium and indium extend the portfolio of incorporated critical raw materials. However *criticality of functional materials* necessitating those raw materials in order to be produced is determined to be low after consultation of market reports. Those reports gave no indication of any increased criticality regarding functional materials such as substrates, LED dies or light converting materials. (DOE 2012; European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015; LED professional 2016a; DERA 2016, pp.88-91)

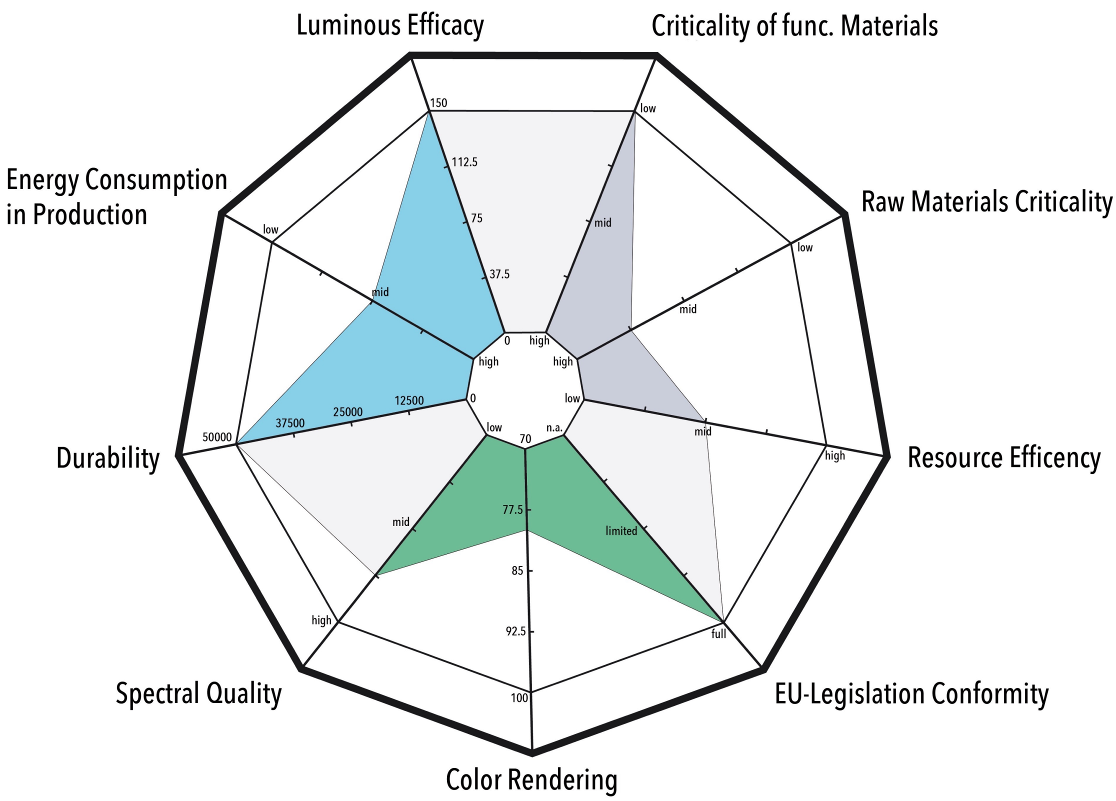


Fig. 55: Assessment results OSRAM Substitube Advanced.

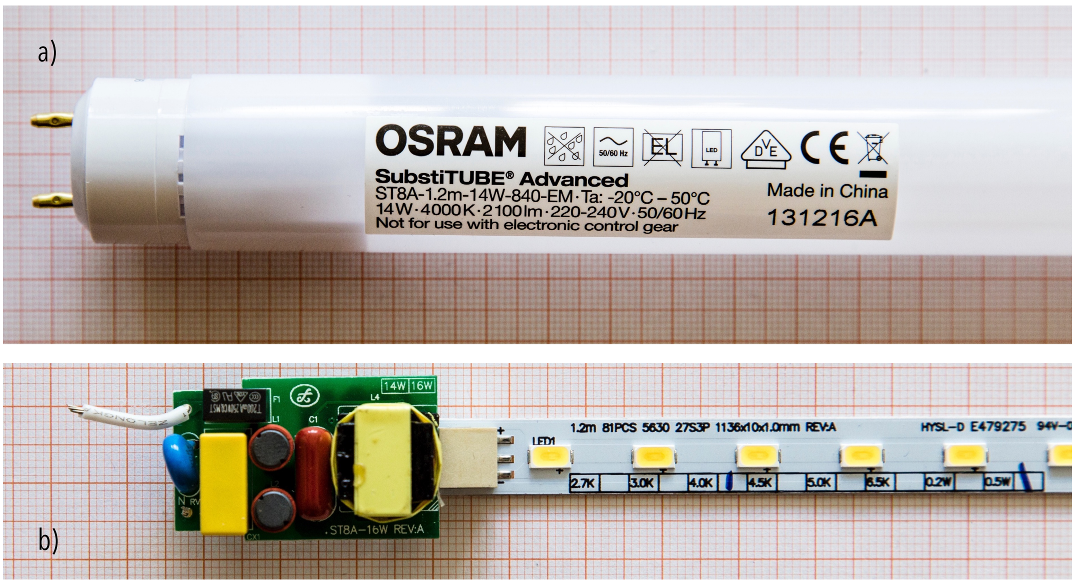


Fig. 56: OSRAM Substitube Advanced.

a) Product before disassembly.

b) Electrical driver unit and SMD LED strip after the non-destructive removal of the tubular PVC-housing.

12.3 Public Lighting

The results of the lighting systems for public lighting are described in the following section. It contains two different types of luminaires. A conventional high pressure sodium vapor lamp and an LED pole light, both designed for street lighting in public areas respectively. In the course of research conducted for this treatise, the consultation of the head of the lighting department Mr. Markus Furnier at the civil engineering office of the city of Augsburg, Germany led to the choice of the respective systems. Sodium vapor lamps currently provide the bulk of streetlamps within the municipal area whereas new installations are equipped with LED technology. Those street lamps could not be acquired for disassembly due to financial reasons, but a close investigation was made possible by the personnel of the city´s civil engineering office. In detail the head of the lighting department recommended both a case lantern fabricated by Philips which uses a replaceable double arch high pressure sodium bulb and integrated street LED street light also manufactured by Philips called Luma Micro. Mr. Furnier pointed out, that those systems feature the most practical relevance because of tool-free maintenance access and their modular layout, making it easy to replace defective components. Also operational versatility and robust design were stated to be advantages of those products.

The following table shows the specifications and order of appearance of the street lamps included in the assessment of light sources for public lighting.

Table 7: Considered light sources for public lighting

	Sodium High Pressure	Philips Luma Micro
Design	Case E27	Integrated
Wattage Equivalent	n.a.	n.a.
Wattage	50 W	12 W
Output	3600 lm	1500 lm
Efficacy	72 lm/W	125 lm/W
CCT	2050 K	4000 K
CRI	20	80
Durability [h]	40000 h	100000 h
Cycles	n.a.	n.a.
Temperature Range	n.a.	n.a.
Socket	E27	Integrated
Beam Angle	n.a.	n.a.
Energy Class	A	n.a.
Price	n.a.	n.a.
Origin	Belgium	n.a.

12.3.1 High pressure Sodium Vapor Street Lamp

The high pressure sodium double arc burner of this lamp features an *efficacy* of 72 lm/W. This value lies below the performances achieved by modern LED street lighting systems. With respect to *energy consumption during production* this illuminant is considered to feature a favorable setup. To grant comparability, the actual light source is assessed apart from the casing necessary for continued outdoor application and the internals also needed in solid-state street lighting. According to a life cycle analysis conducted by the DOE the sodium double arc bulb is assumed to require considerably lower amounts of energy than a comparable LED module. The *durability* of the used high pressure sodium bulb is specified with an average of 40000 hours of operation. If failure did not occur after that period of time, the light output is specified to have dropped below 70% of the initial value. This period of operation is clearly surpassed by modern LED street lamps by at least the factor of two. (Sylvania 2017; DOE 2012; OSRAM 2009; Baer et al. 2016, p. 212)

With regard to *spectral quality* the sodium high pressure lamp features a discontinuous spectrum which is dominated by multiple sharp peaks in the visible spectrum spanning from yellow to red. Additional small peaks can be found in the blue portion of the spectrum. Those properties strongly diverge from daylight conditions and do therefore poorly support the abilities of the human visual apparatus. As a result capabilities of *color rendering* are significantly reduced. The color rendering index lies at 20 which is low in comparison to modern LED streetlights. However those lamps provide good perception of contrasts despite their low performance in terms of color rendering. Regarding *compliance to EU legislation* no current infringements to existing regulations exist. Mercury content of 14.4mg per double arc burner and low efficacy however may result in mid-term restrictions leading to a ban of this technology. (Sylvania 2017, Baer et al. 2016, pp. 212ff.; Aura Light 2017; European Union 2003, 2006, 2009b, 2012c)

With respect to *resource efficiency* this lamp shows a maintenance friendly modular layout. The lamp housing can be opened by hand and internal components are individually replaceable in case of malfunction. Functional components such as ballast, power switch and transformer feature simple yet durable design. The twin arc burner does not necessitate any additional parts in order to be cooled. Concerning production losses, this luminaire is assumed to be a product of efficient manufacturing processes. Materials such as metals, glass and ceramics do not exhibit intricate compositions and are products of mature large-scale industrial processes. Described components are easy to be disassembled and can hence be recovered by recycling processes intended for electrical devices. As to *raw materials criticality* the only material incorporated in this system rated as moderately critical is tungsten. Overall criticality was therefore determined to be low. Since no materials, which comply with the definition of functional material made in this work are comprised within this lighting system, *criticality of functional materials* was determined to be insignificant. (Baer et al. 2016, pp. 210ff.; European Commission 2014; Zepf et al. 2014)

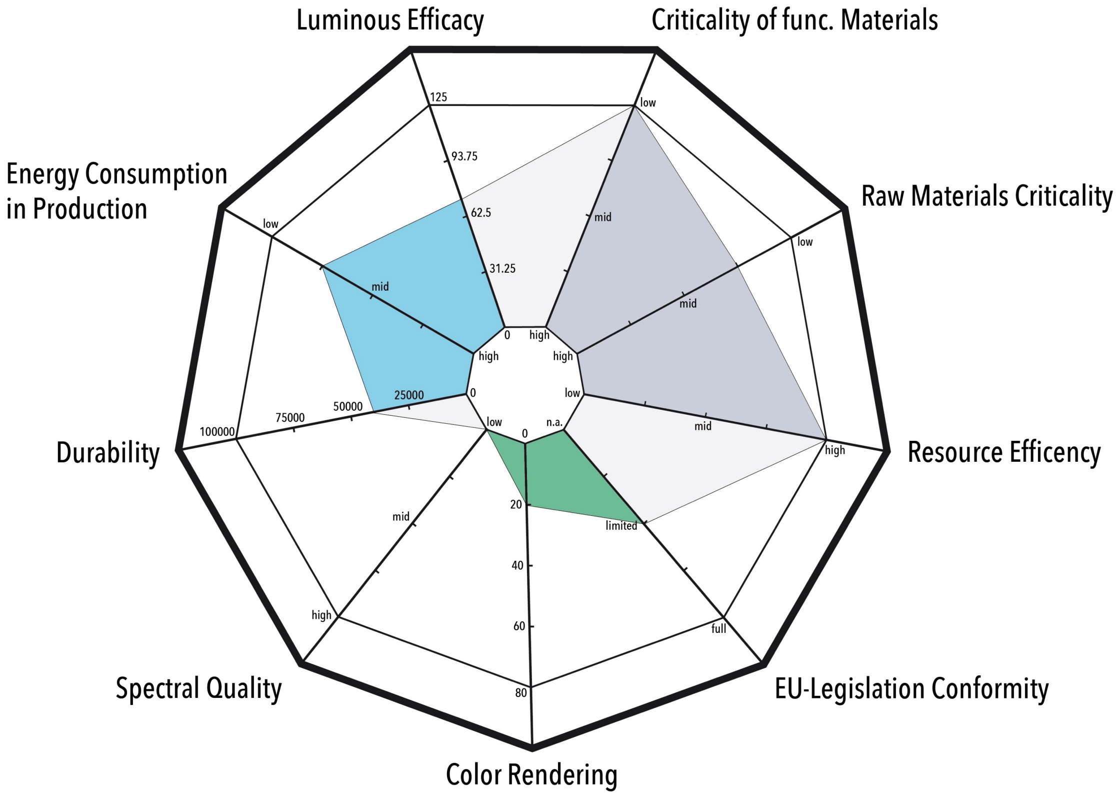


Fig. 57: Assessment results High Pressure Sodium Vapor Lamp.

Fig. 58: High pressure sodium vapor lamp.

a) Modular setup of functional components and seals of the opened tool-free access housing.

b) Edison socket twin arch burner and reflector cup.

12.3.2 Philips Luma Micro LED Street Lamp

This integrated LED lighting device offers an *efficacy* of 125lm/W. This value surpasses the values reached by conventional high pressure sodium vapor lamps. Regarding e*nergy consumption during production* this solution requires increased amounts of energy in comparison to a high pressure sodium vapor lamp. Separate from the sealed casing and internal functional components also required in aforementioned system, the incorporated LED module accounts for elevated energy demand. The service life of this illuminant is specified by the manufacturer to be 100.000 hours in continuous operation. This value significantly surpasses the period of operation achieved by traditional light sources intended for outdoor use. (OSRAM 2009; DOE 2012; Philips 2016a-b)

Since no information about the *spectral quality* of this lighting system could be attained, the determination of its performance is based on the assumption that it relies on an array of blue emitting LED dies complemented by a broadband yellow phosphor. The assumed setup represents the current state of technology as well as the most efficient large scale solution to date. It features a continuous spectrum with an emission peak in the blue region of the visible spectrum, deficits in green and deep red color emission and a broad yellow peak. The spectral distribution is hence superior to the emission of reddish yellow light by sodium vapor lamps on grounds of strongly increased resemblance to light conditions found during daytime. *Color rendering* capacities also lie considerably above those reached by high pressure sodium lamps (CRI 80 at 4000K CCT). With respect to *compliance to EU legislation* this lighting system shows complete conformity to current rules and regulations. No introduction of mid-term restrictions is expected to occur. (European Union 2003, 2006, 2009b, 2012c; Baer et al. 2016, pp. 262ff.)

In terms of *resource efficiency* this illuminant stays behind the performance achieved by the high pressure sodium vapor lantern described above. Like the sodium lamp this LED streetlight offers tool-less access to its modular internals. Components such as the LED-module, the electrical driver unit and optical attachment can be replaced independently and quickly. However especially the LED-module consisting of a heat conducting aluminum carrier plate with surface mounted LED chips is assumed to fundamentally contribute to elevated production losses in comparison to its sodium vapor counterpart. Due to the maintenance-friendly layout of this lighting system retrieval of functional units is easy to perform. The further disassembly of those units, for example the removal of LED dies from their carrier board in end-of-live devices is also a simple mechanical task. Nonetheless the recovery of functional materials from extracted LED dies requires refined recycling processes. As to *raw materials criticality* this luminaire contains the elements indium, gallium and rare earth metals, which are rated as critical by the publications used as source of information for this treatise. In this respect criticality is increased in comparison to a sodium vapor lamp comprising the less critical tungsten as electrode material for its arc burners. Even though some raw materials, which constitute the basis for the fabrication of functional materials are rated as critical, *criticality of functional materials* was determined to be low. Research for this work gave no evidence of problems in supply but rather point towards production ramp up, overcapacity and price decline. (DOE 2012; European Commission 2014; Zepf et al. 2014; LEDinside 2014a-b, 2015a-b, 2016, 2017a-b; Virey 2012, 2015; LED professional 2016a; DERA 2016, pp. 88-91)

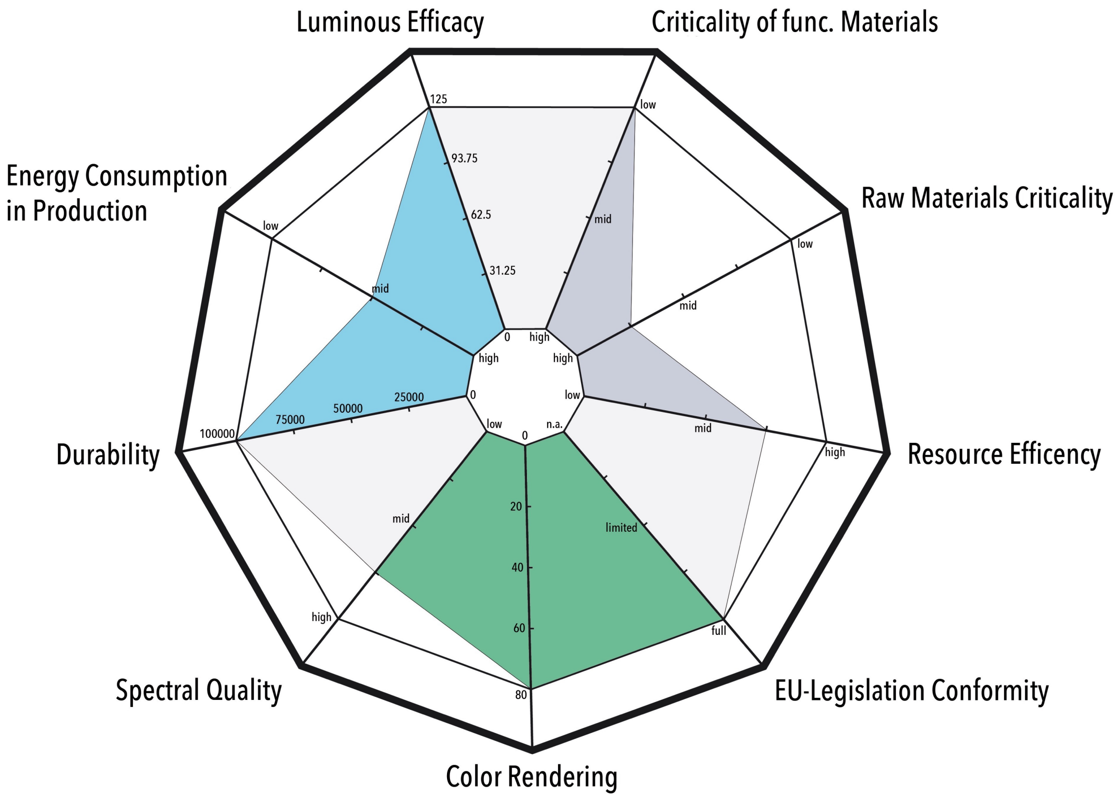


Fig. 59: Assessment results Philips Luma Micro.

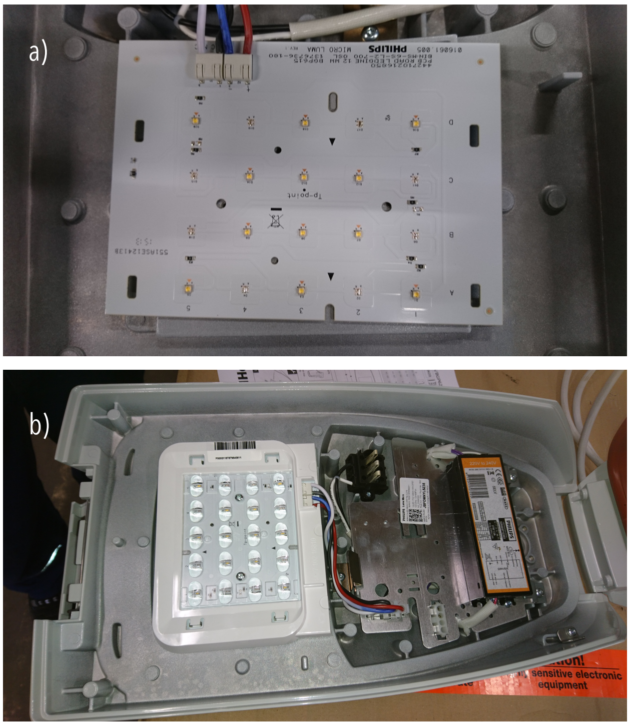


Fig. 60: Philips Luma Micro.

a) LED module.

b) Modular setup of the functional components inside the tool-free accessible aluminum casing. Plastic lens attachment for enhanced light distribution is still in place.

13 Discussion of Results

A comprehensive discussion of the results obtained in the preceding assessment is presented in this chapter. It shows the same structure regarding the sequence of lighting systems considered. First the results of illuminants for domestic lighting ordered according to general working principle and technical implementation are presented. The same procedure is applied for lighting systems for industrial/commercial lighting and lamps for public lighting. In addition to the discussion of the assessed technical solutions, a description of the the disassembly process is included for every sector of use. Here the gained insights regarding basic construction of the included illuminants, estimates about their recyclability and a rating of the quality of technological implementation are given. A section with statements about the technological persistency of the considered lighting systems completes the discussion in each sector of use. The chapter is concluded by a comparison of the technologies included in this work followed by a representation of the interconnections among the used assessment factors and a final section comprising the reached conclusions.

13.1 Domestic Lighting

13.1.1 Incandescent Lamps

The principle of thermal light-emission bears disadvantages in comparison to newer lighting technologies. Most of all in terms of *efficacy* and *durability* this technology shows substantial drawbacks compared to compact fluorescent lamps and LED illuminants. On the other hand, their comparably simple working principles and technical layout make incandescent lamps a favorable choice with respect to production expenses and materials consumption. Also with respect to *spectral quality* they exhibit characteristics, which make them suitable light sources for domestic use. Their spectral properties are in close resemblance to those of daylight (during evening hours) and color-rendering capabilities are still used as a benchmark for other lighting technologies. Furthermore incandescent lamps feature low degrees of resource criticality concerning the materials involved in their production. However, based on their poor performance with respect to in-use energy consumption, the European Union issued a ban forbidding their use in general domestic illumination. This legal action represents a criterion for exclusion with regard to further use in one of the most important economic areas of the world.

13.1.2 Compact Fluorescent Lamp

The compact fluorescent lamp determined to be representative of the current state of technology in domestic lighting features medium performances with regard to *luminous efficacy* and *durability*. It shows considerably higher performances in comparison to incandescent lamps but is also clearly outperformed by the best performing LED systems in this assessment. Furthermore energy expenses for production are assumed to lie between those necessary for incandescent lamps and LED devices. Regarding the efficient use of materials, technical layout, production losses and recyclability were also determined to feature medium performances. Aside from contents of rare earth metals, which are rated as critical in relevant publications, no evidence for supply problems on the basis of raw materials criticality or criticality of functional materials could be identified. With respect to spectral properties, the emission characteristics of this technology exhibit deficits compared to those of incandescent lamps. Capabilities of color rendering are acceptable and correspond to the current state of technology of LED lamps. As to compliance to EU legislation, CFLs are presently in accordance with lighting regulations. However accordance is only reached due to an exception for contents of mercury, which could be revoked on a mid-term basis. (Haitz and Tsao 2010; McKinsey 2012)

13.1.3 LED Lamps

The solid-state lighting devices in this assessment offer best performances with respect to *luminous efficacy* and *durability*. Those two aspects represent the strong points of this technology offering values that clearly exceed the performances of incandescent lamps and compact fluorescent lamps. Nevertheless, LED illuminants do necessitate the largest amounts of energy in production. Due to their comparably complex structure, they incorporate a variety of functional components. Most considered devices feature technical layouts, which result in an increased demand for energy-intensive materials. Moreover, especially light emitting LED dies stem from processes that are accompanied by heightened production losses. Great variety in technical setup among the evaluated lamps causes diverse performances in terms of recyclability. Some lamps are easy to dismantle in order to be delivered into recycling processes while others show impeded extraction of functional components. The fabrication of LED lamps requires the use of several raw materials rated as critical by relevant literature. Although materials like indium, gallium and rare earth elements are considered to be critical, research for this work found no evidence that functional materials fabricated under their use exhibit any indications of criticality. Depending on the basic working principle, LED devices for domestic use offer a diverse set of spectral properties. RGB-based systems show a band spectrum similar to fluorescent lamps whereas phosphor converted systems offer continuous spectra that can get close to the properties of thermal emitters. Color rendering of all evaluated lamps is in an acceptable range for domestic applications. EU legislation currently does not contain any restrictions on the sale and handling of LED light sources for domestic use.

13.1.4 Disassembly

During the research for this treatise most of the illuminants included have been privately purchased and disassembled in order to gain insights into their technical setup. Only the compact fluorescent lamp (OSRAM Dulux Superstar) was not taken apart because of possible mercury release. Also the Philips Hue RGB-system was not purchased due to financial reasons. In this case, internet research provided detailed pictures of a disassembly process, which then were used as basis for assessment. The included LED luminaires showed a broad variety of technical layouts. Basic components such as LED packages, electric driver units, heat sinks and casings exhibited a set of different individual formats.

This variety of technical execution illustrates that LED lamps for domestic use are still in a state of development. Technical solutions and functional approaches are subject to continuous evolution.

Most of the systems still utilize classical surface mounted chips acting as directional light sources. However the implementation of this principle varies in quality. The VOLTOLUX spotlight features 30 individual LED dies concentrically arranged on an aluminum carrier plate. Approximately the same light output is achieved by the OSRAM LED Star spotlight, which only employs a single SMD-LED package of eight combined dies.

This difference in layout and use of resources is one of the most prominent examples regarding state of development and technological sophistication found in this work.

Furthermore both lamps hold strongly differing constructions in respect to thermal management and casing. While VOLOTLUX employs a finned aluminum casing in order to dissipate heat from its functional components, OSRAM incorporates those components into a standard glass casing for halogen lamps. Increased overall device efficiency and resource efficiency are the result.

Also with respect to the design of electric/electronic components the comparison between those two products proves suitable to illustrate basic differences in construction. OSRAM incorporates the LED package and electrical driver unit on a single integrated circuit board. The VOLTOLUX product on the other hand is equipped with a separate small circuit board fitted with through-hole electrical components apparently soldered by hand.

Another illustrative comparison can be made between a frosted bulb design and an LED filament model both manufactured by OSRAM. A fundamental difference between those two lamps lies in the arrangement of light emitting diodes. The frosted bulb LED Star Classic is furnished with an integrated circuit board that carries 17 surface mounted LEDs. Opposed to that the LED retrofit classic is equipped with six LED filaments. Due to enhanced convection effects around the freestanding LED filaments, this design does not require the use of a heat sink. In contrast the frosted bulb design uses an aluminum cup in mechanical contact to an inner aluminum casing in order to grant thermal management of the whole device.

Moreover the filament design holds advantages with regard to light distribution. Since the SMT dies of the frosted bulb represent directional emitters, which have to be distributed by the optical properties of an opaque plastic cup, the special arrangement of the LED filaments allows for the use of a clear glass bulb. This not only results in a more spherical emission pattern but also minimizes absorption losses. Apart from an increased number of smaller LED dies necessary in filament designs this concept is considered to be superior in terms of efficient use of materials and overall device efficiency.

Another aspect, which became noticeable during the selection, purchase and disassembly of LED filament lamps was modularity. According to the offered luminous flux of a lamp the number of filaments incorporated in the device changed while maintaining the same efficacy. Thereby production processes are made more efficient since only small adaption is necessary for the manufacturing of lamps with varying figures of output.

With regard to the Philips Hue smart lighting system the following observations were made: This lamp features considerably increased device complexity in comparison to the other LED lamps in this assessment. Wireless communication and electronic emission control for an array of differently colored chips require elaborate internal components. Apart from that, the layout resembles the setup found at the aforementioned frosted bulb produced by OSRAM. A circuit board comprising surface mounted LED chips of red, green and blue color is placed on an aluminum cup, which is fitted within the actual aluminum lamp casing. This way excess heat during operation can be dissipated via the casing of the lamp. Functional versatility of this product is achieved by increased usage of resources.

13.1.5 Technological Persistency

The determination of technological persistency for each lighting technology considered in the foregone assessment proves to be a complex task. Not only the performances the respective light sources achieve with regard to the applied sub-factors but also their interaction with external factors has to be taken into account.

Despite their advantages, incandescent lamps and halogen lamps suffer from substantial deficits that strongly oppose continued application. In the face of increasing industrialization and a growing world population, the efficient use of energy becomes a fundamental goal of sustainable development (v. Hauff 2014). The incandescent lamp is nowadays significantly surpassed by newer technologies such as fluorescent lamps and solid-state lighting devices. This fundamental drawback of an otherwise well performing technology has a strongly detrimental effect on its technological persistency. Low luminous efficacy of this concept resulted in measures of legislation to advance its phase out. A ban on sale and distribution of incandescent lamps for general domestic lighting confines them to special applications and decorative purposes (European Union 2012b) (EC No 1194/2012). This legal measure acts as a criterion for exclusion regarding its sustained use within one of the most important economic areas of the world. Technological persistency was therefore determined to be very low within the European Union due to this dramatic loss of relevance.

The extensive introduction of compact fluorescent lamps has its origin in the goal to reduce energy consumption in mainly domestic areas of lighting. Functional shortcomings in comparison to incandescent lamps such as discontinuous emission spectra and comparably low color rendering were considered acceptable due to raised efficiency and durability. Also increased energy consumption in production, added device complexity and the incorporation of critical materials represent a regression with respect to the assessment factors used in this work. Moreover the compact fluorescent lamp is currently not subject to legal restrictions. However toxic mercury content and advancements in solid-state lighting technology are expected to lead to a phase out of this technology. In the face of toxicity and outdated efficiency the technological persistency of this technology was determined to be low to medium. (Haitz and Tsao 2010)

Compared to an incandescent lamp, LED lamps show inferior performance with regard to six out of nine sub-factors used in this assessment. However they do offer two distinct strong points with respect to important external factors. The objective of climate protection and the finiteness of fossil resources presuppose the extensive use of energy efficient and long lasting technologies. Solid-state lighting devices exhibit unprecedented capacities in terms of efficacy and durability. Corresponding the goal formulated by the European Union to significantly reduce CO_2 emissions in the course of power generation, highly efficient light sources, which provide extended phases of use are

endorsed by EU legislation. In this context, LEDs and OLEDs are the only technologies that currently comply with the planned tightening of legislation on energy efficiency and content of toxic materials. Yet gains in efficacy, durability and non-toxicity are associated with added device complexity and the consequent disadvantages in resource demand. The use of critical raw materials represents a possible threat to comprehensive availability of solid-state lighting in the future. In order to ensure technological persistency investments in energy and materials have to be kept as low as possible to provide a lighting technology that can be dominant on a global scale. Accordingly different qualities of implementation result in varying degrees of persistency. Solutions like the VOLTOLUX spotlight feature low performance with regard to efficient usage of resources. On the other hand, the latest generation of premium LED lamps offers reduced resource consumption in combination with highly acceptable properties of light emission. Therefore the determined range of technological persistency achieved by the lamps included in this work reflects the circumstance that LED lighting is still a young technology undergoing a rapid process of development. Different grades of sophistication of the assessed lamps cause the technological persistency of domestic LED lighting to range from medium to high.
As a result the technological persistency of LED lighting for domestic use is not exclusively determined by the common strengths of this technology, but also by its implementation. Beyond fulfilling criteria for exclusion such as efficacy, durability and toxicity the magnitude of investment in energy and resources decides over success or failure in establishing solid-state lighting as prevailing lighting technology.

13.2 Industrial/Commercial Lighting

13.2.1 Fluorescent Lamps

The fluorescent lamps in this evaluation were picked to be representative of the current capabilities of an established and mature technology. They offer high values of efficacy and acceptable durability. With regard to energy consumption during production they are assumed to require significantly less energy in comparison to their LED counterparts. Also their technical layout and production processes were determined to be resource efficient. Recyclability of those lamps suffers from mercury contamination of phosphor materials and thus hampered retrieval of contained rare earth elements. Moreover the incorporated rare earth elements are rated as critical by relevant literature. However research for this work brought no indication of phosphors to show characteristics of critical functional materials themselves. The considered illuminants feature spectral properties dominated by a band spectrum. Despite deficits in spectral distribution those lamps are capable of achieving acceptable to high color rendering indices. Regarding conformity to EU legislation, it should be noted that fluorescent tubes are subject to exception of the RoHS directive due to mercury content. Otherwise this technology is in accordance to European law but may be phased out in favor of non-toxic solid-state lighting solutions on a mid-term basis.

13.2.2 LED Tubes

The LED tube lights considered in this work clearly surpass fluorescent lamps in terms of efficacy and durability. Regarding energy consumption during production, they are assumed to require significantly higher quantities of energy due to complex manufacturing processes. In view of their technical layout, which necessitates a higher number of functional components in comparison to fluorescent tubes, resource efficiency is assumed to be lower. Moreover especially the production of the numerous LED dies included in an LED tube is assumed to implicate elevated production losses. Disassembly of the evaluated products however revealed good access to functional components, therefore alleviating their introduction to recovery processes. In addition to rare earth elements also contained in fluorescent tubes, LED tubes comprise indium and gallium. Those raw materials are considered to be critical. Nevertheless criticality of functional materials was determined to be low. The spectral properties of the considered lamps outmatch those of fluorescent lamps due to a more continuous emission spectrum. However color-rendering capabilities are equal or inferior to the fluorescent tubes included in this evaluation. Conformity to EU legislation is granted in every aspect.

13.2.3 Disassembly

The dismantling of both LED tubes included provided insights regarding the technical layout of one low-priced and one high-priced product currently offered by two of the market leading companies OSRAM and Philips.

The low-priced Philips product employs a glass tube structure similar to a fluorescent lamp featuring a glued in LED-strip with 70 surface-mount packages. The end-caps containing the electrical driver unit and mounting contacts are cemented to the coated glass tube. It is assumed that the internal coating of the tube, used to enhance light distribution by scattering, is the same as the phosphor carrying filler material in fluorescent lamps. No heat sinks are included. Due to the grade of mechanical connection provided by the strong adhesive bonds between single components, disassembly for recycling might be impeded.

In contrast to the previously described glass structure, the high-priced LED tube manufactured by OSRAM features a polycarbonate tube with a slide-in bracket for the embedded LED strip. The strip itself is equipped with 81 SMD packages of comparably low luminous flux. Also the end caps are attached by a plug connection without the usage of any glue. This modular and easy to disassemble design has beneficial effects for end-of-life recycling on the basis of quick and tool-free disassembly of structural and functional components.

Regarding the setup of the included fluorescent tubes, the nearly identical layout of both products considered allows a combined treatment. Both luminaires consist of evacuated glass tubes filled with a small amount of mercury (Philips TL-D ECO: 2.0mg, Philips TL-D De Luxe: 3.0mg) and diverse noble gases (Baer et al. 2016, pp. 200ff.; Philips 2017b-c). The inside of the glass tube is coated with filler that incorporates the light converting material. In comparison to an LED tube light, the complete coating of the tube requires usage of higher amounts of phosphor.

The glued-on end caps house heated electrodes, which are used to induce and maintain gas discharge within the tube. Due to the fragility of the glass tube and its airtight adhesive bonds to the end caps, disassembly for recycling necessitates the use of dedicated machinery. Mercury content prohibits manual handling during the first steps of recycling. (Lightcycle 2017)

13.2.4 Technological Persistency

Similar to the evaluated systems for domestic lighting the strong points and weaknesses of LED-based luminaires depend on technical implementation. The degree of technical sophistication determines to which extend advantages can be harnessed and deficits can be mitigated. The OSRAM Substitube LED tube for instance delivers performances with respect to efficiency and durability that considerably exceed the values achieved by the fluorescent tubes and the second LED tube considered in this assessment. Also its expected long-term compliance to EU legislation on grounds of non-toxic content is a factor, which adds to the overall technological persistency of this solid-state lighting device. In view of the declared objective of the European Union to consistently reduce the energy consumption in lighting the most important prerequisites are thereby fulfilled. Nevertheless uncertainties are caused by the content of raw materials, which are rated as critical. Problems in supply or price volatility can exert detrimental effects on the availability of LED luminaires. The same extenuated effects though might affect the production of fluorescent tubes due to content of rare earth metals. Higher expenses of energy during production and reduced resource efficiency compared to fluorescent lamps are relativized by substantially longer phases of use. Seeing that mostly external factors like climate protection and consumer protection are dominant aspects that grant the persistent application of solid-state lighting it is also important to consider functional benefits. The spectral properties of LED tubes are favorable over the band spectra of fluorescent lamps especially under long time exposure found in industrial environments. Here the spectrum is assumed to be more agreeable and to cause less health related issues in the work force. (Boyce 2014, pp. 91ff.; Khanh 2015, pp. 44ff.)

13.3 Public Lighting

13.3.1 High Pressure Sodium Vapor Lamp

The considered high pressure sodium vapor lamp offers state of the technology values of efficacy. Operational durability of this mature technology is specified to reach appropriate durability in outdoor operation. A long lasting sealed casing and modular setup of functional components constitutes a resource efficient layout. Production of those components is assumed to exhibit smaller production losses than a comparable LED street lamp. Modularity also grants eased retrieval of internal components for recycling purposes. The examined lamp contains neither critical raw materials nor functional materials as defined in this work. Its spectral distribution is incomplete offering only significant output in the yellow to red portion of the visible spectrum. Furthermore this technology offers poor capabilities of color rendering.

13.3.2 LED Street Light

The Philips Luma Micro provides substantially higher efficacy in comparison to a conventional high pressure sodium vapor lamp. Furthermore it offers a considerably extended and easy to maintain use phase. With regard to resource efficiency, the modular setup of internal functional components represents a resource efficient solution. Production losses are assumed to be elevated on grounds of resource-intense LED die manufacturing. Preparation of this luminaire for recycling is facilitated by partially tool-free disassembly and clearly separated functional units. Raw materials criticality is heightened in comparison to sodium vapor lamps due to an increased number of contained critical materials. Criticality of functional materials was however determined to be low. The spectral properties of this lighting device are favorable in comparison to conventional street lighting technologies. Also color rendering meeting standards for domestic lighting provides benefits for the lighting of streets and public areas. Conformity to EU legislation is currently granted with no official statements on impending restrictions.

13.3.3 Disassembly

By courtesy of the staff of the civil engineering department of the city of Augsburg both street lights described above could be closely examined. Noticeable for those products are sturdy sealed cases providing extensive protection for internal components against environmental influences and the intrusion of attracted insects. Furthermore both devices feature a strongly modular internal setup allowing for quick change of failed structures. In this respect especially the modularity of the examined Philips Luma street light gave clear hints for potential modifications. Comprised LED modules are quickly exchangeable in order to alter luminous flux and desired spectral properties. Beyond that the optical unit, a transparent sheet of plastic with integrated lenses, is easily interchangeable for modifications regarding the emission pattern of the lamp. This way the illumination of public spaces and streets can be adapted to changing lighting requirements.

13.3.4 Technological Persistency

Comparison of the evaluation results of both street lights examined proves the LED street lamp to be the preferable solution. Strong advantages in terms of luminous efficacy and light quality (spectral quality and color-rendering) complement high-grade durability resulting in superior in-use characteristics. The considerably longer use phase facilitated by the integrated LED module and the long lasting aluminum casing however relativize shortcomings in terms of both energy consumption and efficient use of resources during production. In view of the long-term investment that the acquisition of street lights represents operational benefits such as mentioned gain importance. With respect to materials supply LED based systems face the problem of possible shortages due to the use of critical raw materials. Yet the supply of functional materials, which constitutes an important factor in the production chain was determined to be non-critical.

With regard to the pursued objective of reduced energy consumption within the European Union energy savings, especially in extensive use encountered in street lighting, are able to make a great contribution. This circumstance finds its legal implementation in EU legislation advancing the phase out of sodium vapor street lamps. In consequence the clear operational benefits of LED street lighting and the current legal framework result in high technological persistency of solid-state lighting solutions.

13.4 Comparison of Technologies across Sectors of Use

The assessments conducted for three different sectors of use revealed basic advantages and disadvantages of the different lighting technologies considered. The following section is intended to sum up those findings in a comparative way across all sectors of us incorporated in this work.

13.4.1 Energy

With respect to the core-factor energy, the evaluated solid-state lighting systems deliver the best performances in terms of efficacy and durability. Ranging over all sectors of use (i.e. domestic lighting, industrial/commercial lighting and public lighting) LED-based lighting systems surpassed conventional technologies such as incandescent- and gas discharge lamps. The excellence in providing highly efficient long lasting emission of light is the most apparent quality of LED technology.

However as result of added device complexity and intricate combination of highly specialized materials, energy consumption during production is considerably increased compared to traditional light sources. This circumstance is most apparent in domestic lighting where incandescent lamps require significantly smaller amounts of energy in order to be produced. However this drawback is mitigated by the superior phases of use achieved by solid-state lighting. This especially applies to sectors of use where extended use-life is a key criterion: Use phases of 100.000 hours of continuous operation and a smaller contribution of the fitted LED module to the overall production expenses required for an integrated street lamp, accelerate the amortization of initially higher amounts of energy consumed in production.

13.4.2 Function

Incandescent lamps feature the most favorable characteristics with respect to spectral quality and color rendering. The gas discharge based luminaires in this evaluation show mostly incomplete emission spectra. Especially in street lighting the widely established high pressure sodium vapor lamp offers only poor spectral properties and color rendering. LED lighting provides acceptable performances across all sectors of use offering suitability for low- as well as high-output applications. The pursued phase out initiated by the European Union greatly diminishes the current and future relevance of incandescent systems in all lighting applications. Also gas discharge lamps are already subject to legislation measures advancing the gradual phase out systems featuring low efficiency. Moreover the mercury content of those luminaires is assumed to be a reason for accelerated phase out those technologies once solid-state lighting reaches a state of high affordability.

13.4.3 Materials

Similar to the described deficits of-solid state lighting with regard to energy consumption during production the comparably complex design of LED luminaires requires elevated input of materials. Lossy production processes and the highest number of incorporated critical materials in comparison to the other lighting technologies included in this work represent disadvantages across all sectors of use.

13.5 Interconnections

The assessment results of light sources across all sectors of use show correspondence to the theoretical considerations made in this work. Dynamic interconnections among the core-factors of technological persistency become apparent in the performances of actual illuminants. Closer inspection of the results shows how variations in performance regarding the core-factor energy correspond to a shift of ratings regarding the core-factors material and function. Similar effects can be observed vice versa. On an inter-technological level, the striving to create lighting infrastructure facilitating more efficacious transformation of energy into usable light entails an increase in device complexity. This has consequences regarding functional aspects and usage of materials. The mentioned increase in complexity, which accompanies the evolution of lighting systems from incandescent lamps over gas discharge lamps to solid-state lighting illustrates those circumstances. Every step of technological development is followed by increased content of functional materials necessitating a greater variety of critical raw materials. Also the objective to save energy in lighting affects the qualities of light that can be achieved. Elevated efficacy is reached on account of spectral properties and color rendering.

Those correlations directly apply on an intra-technological level as well. Especially in solid-state lighting with its current multiplicity of technological implementations mutual interactions become evident. Enhanced functional qualities for instance have detrimental effects on the efficacy of an LED lamp. A Luminaire like the Xavax High Line featuring improved spectral qualities and color rendering offers inferior luminous efficacy in comparison to the other included LED retrofit bulbs. Also the considered smart lighting solution manufactured by Philips, which provides a variety in color emission and color correlated temperature falls short in terms of efficacy. Both lamps moreover illustrate the connection between functional aspects and materials usage. In their respective cases, enriched color emission and extended functionality result in added complexity and higher overall content of functional materials. Another important connection was identified with respect to durability of LED lamps. Luminaires featuring the longest specified phases of operation for domestic and industrial use exhibit an increased number of low-output LED dies. This means that raised durability is accompanied by higher initial expenses of resources and energy during production.

13.6 Conclusions

Not only the luminous efficacy and the functional qualities of a luminaire decide over its capability to offer sustainable generation of synthetic light. Technological persistency is reached when the made investments in energy and materials during production yield favorable performance. According to the rating concept developed in this work, technological persistency is a comparative quality. Results of evaluation are not to be seen as absolute, but need to be regarded in relation to other solutions available. The superior performance of solid-state lighting systems in comparison to gas discharge lamps (fluorescent lamps, CFLs and sodium vapor lamps) and incandescent lamps with respect to efficacy and durability fulfills two important premises. Furthermore their acceptable to highly acceptable functional properties grant the fitness for sustained application in a variety of scenarios. Moreover conformity to current legal framework grants the application of LED lighting without restrictions. However solid-state lighting is a comparatively complex technology. Intricate highly specialized production processes and functional materials require the input of elevated amounts of energy and a multitude of materials. Increased energy consumption and materials input during production in comparison to conventional lighting technologies represent disadvantageous properties. Conventional light sources provide better characteristics with regard to those respects. In order to represent a sustainable technological lighting solution, LED-based luminaires need to amortize higher investments made in their manufacturing. According to the life cycle assessments used as sources of information for this treatise, the active phase of use constitutes the dominant factor in terms of overall energy efficiency. Correspondingly the assessments made in this work showed that the the combination of both significantly extended phases of use and unequalled in-use efficiency result in an energetically more sustainable arrangement. However the use of critical raw materials, which are also utilized in other high technology branches can be a limiting factor for the extensive introduction of solid-state lighting around the globe. The high degree of technological sophistication of solid-state lighting systems might become a criterion of exclusion for its widespread application. In this regard the technical implementation of solid-state lighting is an aspect of high relevance. The close observation of technical layouts featured by the included illuminants demonstrated a variable relation between resource usage and performance. Advanced more resource efficient setups with decreased content of materials and functional components however represent desirable solutions to mitigate potential disproportions between raw materials supply and demand. In reducing materials demand for the production of single units by refinement of design the vulnerability of solid-state lighting to possible supply shortages can be lowered.

In conclusion, this assessment found solid-state lighting to feature the highest degree of technological persistency among the lighting concepts considered. High efficacy and durability compensate for increased energy consumption during production. LED illuminants feature a broad variety of functional characteristics that make them suitable solutions for domestic, industrial/commercial and public lighting. This unique versatility and the lack of toxic materials promote the replacement of traditional light sources and the use in new installations. At the moment the technology-inherent demand for diverse critical raw materials and the production of intricate functional materials do not represent a problem for the continued adoption of this technology. Moreover a constant process of development in manufacturing techniques and device construction are capable of improving resource efficiency and technical implementation.

14 Outlook

Solid-state lighting is still in a process of continuous development. The enhancement of existing concepts and the introduction of new variations of technical implementation are expected to result in further increases of performance. Rising figures of luminous efficacy that excel most conventional lighting technologies will complement the growing need for energy efficient lighting. Also by providing illuminants of steadily increasing durability further savings of energy will be achieved. Furthermore advancements in manufacturing are expected to increase resource efficiency in solid-state lighting. Refined fabrication of substrates (silicon-based crystal growth) and the use of larger wafers result in larger production yields. Moreover improvements in epitaxial growth of LED chip structures will bring reduced lattice defects thus increasing recombination efficiency. Thermal properties of LED devices are going to benefit from elevated die efficiencies thereby minimizing or superseding the need for heat sinks or other methods of thermal management. More efficient LED dies and reduced need for thermal management will significantly contribute to a reduction in overall resource demand for individual devices. This increase in resource efficiency is too expected to develop sales on grounds of cheaper production and raised affordability. Moreover advancements towards a simplified construction lead to alleviated retrieval of functional components for recycling. The implementation of novel phosphors will also facilitate more saturated emission spectra for better daylight resemblance and improved color rendering. (Haitz and Tsao 2010; DOE 2012; Whitaker 2012; Khanna 2014)

Those developments are all deemed to further increase the technological persistency of LED Lighting. In reference to the evaluation system designed for this work, the described improvements mean a gain for every included sub-factor of assessment. Solely the factors *criticality of functional materials* and *raw materials criticality* are affected in an indirect manner. Since the usage of critical raw materials and intricate functional materials is inherent to solid-state lighting from today´s point of view, progression in resource efficiency will be beneficial for those factors as well. Most notably in the face of rising global demand for LED-based illuminants, a reduction of resource consumption in manufacturing is a constructive development in order to dampen the impacts of vulnerable materials supply.

Apart from the advancement of existing solid-state lighting concepts, novel light converting materials like quantum dot based phosphors could be introduced. Quantum dots are nanocrystals that allow for exact tuning of their emission characteristics. Yet currently high cost of production and difficulties in providing consistent particle sizes hinder large-scale application. Nonetheless they represent a promising approach to create efficient materials for light conversion and are suitable to facilitate selective modifications of emission properties. Furthermore most quantum dot systems do not depend on the properties of rare earth elements but can be synthesized from non-critical materials such as cadmium selenide. (Khanna 2014)

Organic light emitting diodes (OLEDs) may become viable solutions for general lighting in the future. They apply the same basic working principle like inorganic LEDs but feature emission layers made of small organic molecules or polymers. What distinguishes this technology are less intricate fabrication processes, lower cost of materials and the ability to form large uniformly emitting panels. Yet OLEDs currently suffer from drawbacks which are expected to be overcome in the future. The manufacturing of large area panels for pleasant glare-free lighting environments and improvements regarding environmental stability, durability, production expenses and fabrication are estimated to make OLEDs more relevant lighting solutions for the future. Increased efficacy and large area emission will then allow complementary setups of rather directive LED luminaires and OLED panels creating pleasantly illuminated surroundings in domestic and commercial applications. (Khanna 2014)

In addition inorganic laser diode-based lighting may play a role in negotiating limitations arising in high output application scenarios. Due to penalties in efficacy at increased forward currents, a phenomenon called droop, conventional light emitting diodes become uneconomical in high power operation. Laser diodes, which utilize the principle of stimulated emission (opposed to spontaneous emission in LEDs) however show contrariwise behavior under elevated operating currents. Therefore small but powerful laser diodes are able replace LED systems requiring several combined dies to reach the same output. Possibilities for the implementation of laser diode technology in general lighting include additive combination of three primary color lasers or a short wavelength laser diode combined with a downconverting phosphor. Especially in view of the objective to further increase efficiency in lighting, the former concept is promising. Although requiring advanced optics in order to combine coherent beams of differently colored laser light, the elimination of conversion losses in phosphors is a rewarding achievement. (Khanna 2014)

The introduction of integrated lighting systems for domestic lighting will bring further advantages. Lamps with long lasting inseparably integrated LED modules will be able to harness the full potential of this technology while intelligent controls can be used to achieve additional improvements in efficiency. Those intelligent control units detect changes in ambient lighting conditions and human presence and react by switching and dimming of living space illumination.

All things considered, the outlook of this work is that saving of energy will be the dominant criterion for any lighting technology to be of enduring relevance. Not only the objective to save energy with regard to preservation of finite resources but also the mere availability of energy will be decisive for applicability. In the face of progressing industrialization and electrification around the world, infrastructural challenges may also be the reason for accelerated adoption of energy efficient technologies. Rapidly developing countries may not be able to sustain the demands of inefficient processes and therefore lead the way by early adoption during initial provision of infrastructure. At this point, solid-state lighting poses an efficient versatile solution for domestic, industrial and public lighting. In conclusion it is assumed that LED based lighting will become the dominant solution in industrialized countries as well as in emerging markets as those processes continue. However advantageous functional properties and currently unparalleled combination of efficacy and durability may be foiled by issues regarding availability of resources. With increasing adoption of solid-state lighting, resource demand may reach a magnitude that puts pressure on global resource markets. If high criticality, supply shortages and vulnerable prices exert detrimental effects on the production of LED illuminants, other solutions could become competitive again. Conventional technologies like gas discharge lamps or incandescent lamps, which rely on a lesser number of critical raw materials hold advantages in this regard. Nevertheless those potential problems seem to be of little relevance at the moment. The availability of crucial functional materials made from critical raw materials shows no indication of foreseeable shortages. Moreover recycling of those functional materials from end-of-life devices bears the potential to create additional supply from recovered substances.

Picking up the introductory thoughts of this work, LED-based lighting constitutes a powerful piece of infrastructure in the extensive series of energy- and resource transformations that are involved in the provision of synthetic light. If supply of resources is granted with regard to upcoming challenges like competing technologies and considerable expansion of production, solid-state lighting is capable of making comparably high investments of energy and resources worthwhile. Expected upgrades in manufacturing, durability and efficacy will strengthen its position as a persistent technology that is able to significantly contribute to the reduction of global energy consumption.

In a broader sense, the introduction of persisting innovative technologies marks a new chapter in technical history. In this connection, it is worth to be noted that apart from new levels of functionality also new levels of implication are constituted. With respect to the extensive proliferation of solid-state lighting for instance, novel resource strategic implications can form. Often the provision and development of innovative technologies is prioritized over their long-term implications regarding the involved chains of energy- and resource transformation. This may lead to conflicts between functional advantages and their resource strategic effects. Therefore it is important to apply a broader focus in order to re-open the boundaries of a strictly function based approach to create a more holistic outlook. Only by taking the role played by innovative technologies in larger embedded processes into account, one can make funded statements about their suitability to be a part of sustainable development. By widening the scope of consideration, as it is the intend of the methodology applied in this work, it is possible to assess and acknowledge the potential of solid-state lighting to be a sustainable and persistent final link in a chain of sustainable infrastructure.

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